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SIGNAL PROCESSOR PERFORMANCE COMPARISON.(U)

JAN 67 P B BROWN   NOBSR-95149

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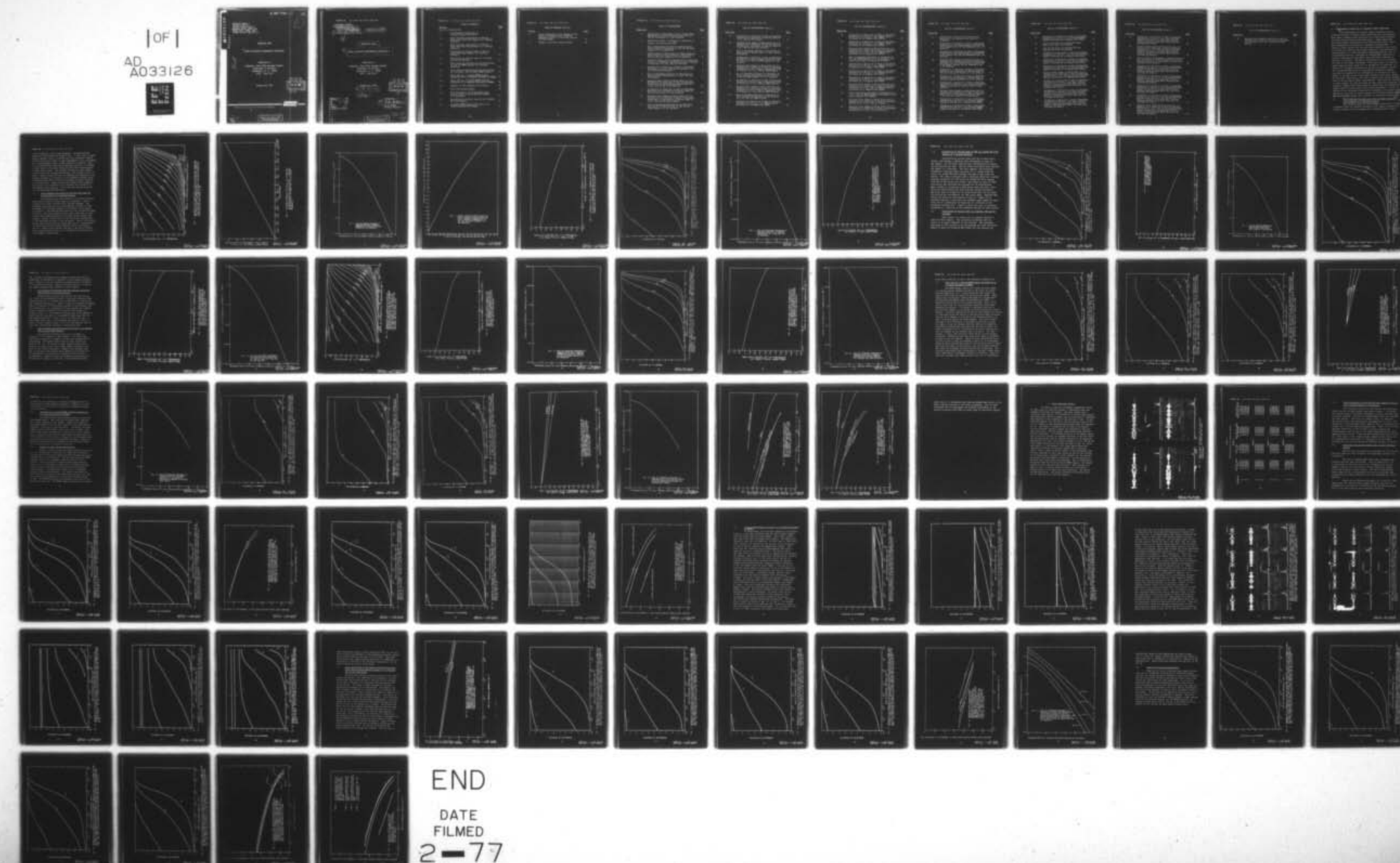

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SIGNAL PROCESSOR PERFORMANCE COMPARISON

Good

Submitted to

Commander, Naval Ship Systems Command
Department of the Navy
Washington, D. C. 20360
Attn: Code 1631

January 26, 1967

TRACOR

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Submitted:

10 Peter B. Brown

P. B. Brown
Project Director

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TABLE OF CONTENTS

Section		Page
List of Illustrations		v
1.	A Performance Comparison of Selected Signal Processors	1
1.1	Fully Coherent Correlation of 200 cps Wide Linear FM Slide Signals of 2 Seconds Duration	1
1.2	Fully Coherent Correlation of 200 cps Wide Ideal FM Slide Triplets of 2 Seconds Duration	2
1.3	Correlation by Partial Sums of 200 cps Linear FM Slide Signals of 2 Seconds Duration	11
1.4	Correlation by Partial Sums of 2 Seconds, 200 cps FM Triplets	11
1.5	Fully Coherent Correlation With OR Circuits of 200 cps PRFM Signals of 2 Seconds Duration	16
1.6	Fully Coherent Correlation With OR Circuits of 2 Seconds, 200 cps Ideal PRFM Triplets	16
1.7	Ideal 200 cps, 2 Second DRTFM Signals Processed as in a Diagram furnished by USNUSL	25
1.8	Ideal 200 cps, 2 Second DRTFM Triplets Processed as in Diagram furnished by USNUSL	30
1.9	Summary of Ideal Signals and Triplets	30
2.	Other Structured Signals	40
2.1	Full Correlation of Jittered FM Slide Signals Using an Ideal FM Slide Signal as a Reference	43
2.2	Correlation by Partial Sums of the Jittered FM Slide Signals	43
2.3	Jittered DRTFM Signals Processed as in Diagram furnished by USNUSL	51

TABLE OF CONTENTS (Cont'd)

Section		Page
2.4	Cross Correlation of the Outputs of Two Replica Correlators Each of Which Operates on Half of a 2 Second, 200 cps FM Slide Signal	61
2.5	Summary of Jittered Signal Results	69

LIST OF ILLUSTRATIONS

Figure No.		Page
1	Probabiilty of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation of 200 cps FM Slides of 2 sec Duration	3
2	Required Increase of $(S/N)_{IN}$ as a Function of Doppler for 200 cps FM Slide	4
3	Rate of Exceeding Threshold vs Threshold for Fully Coherent Correlation of 200 cps FM Slide Signals of 2 sec Duration	5
4	Output Signal-to-Noise Ratio vs Input Signal-to-Noise Ratio for Fully Coherent Correlation of 200 cps FM Slide Signals of 2 sec Duration	6
5	Required $(S/N)_{IN}$ for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation of 2 sec, 200 cps FM Slide	7
6	Probability of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation of 2 sec, 200 cps FM Triplets	8
7	Rate of Exceeding Threshold vs Threshold for Fully Coherent Correlation of 2 sec, 200 cps FM Triplets	9
8	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation of 2 sec, 200 cps FM Slide Triplets	10
9	Probability of Detection vs Rate of Exceeding Threshold for Correlation by Partial Sums of 200 cps FM Slides of 2 sec Duration	12
10	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Correlation by Partial Sums of 2 sec, 200 cps FM Slide Signals	13
11	Rate of Exceeding Threshold vs Threshold for Correlation by Partial Sums of 200 cps FM Slide Signal of 2 sec Duration	14

LIST OF ILLUSTRATIONS (cont'd.)

Figure No.		Page
12	Probability of Detection vs Rate of Exceeding Threshold for Correlation by Partial Sums of 2 sec, 200 cps FM Triplets	15
13	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Correlation by Partial Sums of 2 sec, 200 cps FM Slide Triplets	17
14	Rate of Exceeding Threshold vs Threshold for Correlation by Partial Sums of 2 sec, 200 cps FM Triplets	18
15	Probability of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation with Or Circuits of 200 cps PRFM Signals of 2 sec Duration	19
16	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation with Or Circuits of 2 sec, 200 cps PRFM Signals	20
17	Rate of Exceeding Threshold vs Threshold for Fully Coherent Correlation with Or Circuits of 200 cps PRFM Signals of 2 sec Duration	21
18	Probability of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation with Or Circuits of 2 sec, 200 cps PRFM Triplets	22
19	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Fully Coherent Correlation with Or Circuits of 2 sec, 200 cps PRFM Triplets	23
20	Rate of Exceeding Threshold vs Threshold for Fully Coherent Correlation with Or Circuits of 2 sec, 200 cps PRFM Triplets	24
21	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec DRTFM Signals Processed as in Diagram from USNUSL	26

LIST OF ILLUSTRATIONS (cont'd.)

Figure No.		Page
22	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec DRTFM Signals Processed as in Diagram from USNUSL	27
23	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec DRTFM Signals Processed as in Diagram from USNUSL	28
24	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for 2 sec, 200 cps DRTFM Signals Processed as in Diagram from USNUSL	29
25	Rate of Exceeding Threshold vs Threshold for 200 cps DRTFM Signals of 2 sec Duration Processed According to Diagram from USNUSL	31
26	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec DRTFM Triplets Processed as in Diagram from USNUSL	32
27	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec DRTFM Triplets Processed as in Diagram from USNUSL	33
28	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec DRTFM Triplets Processed as in Diagram from USNUSL	34
29	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for 2 sec, 200 cps DRTFM Triplets Processed as in Diagram from USNUSL	35
30	Rate of Exceeding Threshold vs Threshold for 2 sec, 200 cps DRTFM Triplets Processed According to Diagram from USNUSL	36
31	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for 2 sec, 200 cps Signals	37
32	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for 2 sec, 200 cps Triplets	38

LIST OF ILLUSTRATIONS (cont'd.)

Figure No.		Page
33	Some Typical "Jittered" 200 cps FM Slide Signals of 2 sec Duration and Their Correlograms	41
34	Probability of Detection vs Rate of Exceeding Threshold for Full Correlation of Jittered FM Slide Signals with 200 cps Bandwidth and 2 sec Duration	44
35	Probability of Detection vs Rate of Exceeding Threshold for Full Correlation of Jittered FM Slide Signals with 200 cps Bandwidth and 2 sec Duration	45
36	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Full Correlation of Jittered FM Slide Signals Having 200 cps Bandwidths and 2 sec Duration.	46
37	Probability of Detection vs Rate of Exceeding Threshold for Correlation by Partial Sums of 200 cps Jittered FM Slides of 2 sec Duration	47
38	Probability of Detection vs Rate of Exceeding Threshold for Correlation by Partial Sums of 200 cps Jittered FM Slides of 2 sec Duration	48
39	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Correlated by Partial Sums in Eight Sections	49
40	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for Correlation by Partial Sums of 2 sec, 200 cps Jittered FM Slide Signals	50
41	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered DRTFM Signals Processed as in Diagram from USNUSL	52
42	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered DRTFM Signals Processed as in Diagram from USNUSL	53

LIST OF ILLUSTRATIONS (cont'd.)

Figure No.		Page
43	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered DRTFM Signals Processed as in Diagram from USNUSL	54
44	Four Typical Pairs of Jittered FM Slide Signals and Their Correlograms	56
45	Four Typical Pairs of Jittered FM Slide Signals and Their Correlograms	57
46	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Processed as in Diagram from USNUSL	58
47	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Processed as in Diagram from USNUSL	59
48	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Processed as in Diagram from USNUSL	60
49	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for 2 sec, 200 cps Jittered FM Slide Signals Processed as in Diagram from USNUSL	62
50	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Ideal FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	63
51	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Ideal FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	64
52	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Ideal FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	65

LIST OF ILLUSTRATIONS (cont'd.)

Figure No.		Page
53	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Ideal FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	66
54	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for 2 sec, 200 cps Ideal FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	67
55	Rate of Exceeding Threshold vs Threshold Setting for Correlation of FM Slide Signals in Halves, Envelope Detection of Each Half, and Cross Correlation of the Results	68
56	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	70
57	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	71
58	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	72
59	Probability of Detection vs Rate of Exceeding Threshold for 200 cps, 2 sec Jittered FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	73
60	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding Threshold for 2 sec, 200 cps Jittered FM Slide Signals Processed by Correlating in Halves, Envelope Detecting Each Half, and Cross Correlating the Results	74

LIST OF ILLUSTRATIONS (cont'd.)

Figure No.		Page
61	Required Input Signal-to-Noise Ratio for 0.5 Probability of Detection vs Rate of Exceeding the Threshold for 2 sec, 200 cps Jittered Signals	75

1. A PERFORMANCE COMPARISON OF SELECTED SIGNAL PROCESSORS

The performance of several signal processors used or potentially useful in modern active sonar has been investigated. This report compares these processors on a basis which includes both the output statistics and data rates. These comparisons are based on what are referred to as modified ROC curves, which give probability of detection vs threshold crossing rate. A family of these curves, one for each input signal-to-noise ratio, is required to describe each signal processor. Also included for each processor is a curve giving the threshold crossing rate vs the threshold setting. Although the modified ROC curves give a complete comparison of processors they are rather difficult to evaluate at a glance. Therefore, one further curve is included for each of the signal processors. This curve gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of threshold crossing rate and may be obtained from the set of modified ROC curves by plotting the threshold crossing rate which corresponds to 0.5 probability of detection for each member of the set vs the input signal-to-noise ratio which appears on that curve. Initially, two sets of signals were passed through each of the processors under consideration. The first set consisted of ideal signals for that processor and the second set consisted of composite signals which were formed by adding three overlapped ideal signals with 20 milliseconds delay between components. In the remainder of the discussion these will be referred to as ideal triplets. The results for both the ideal signals and the ideal triplets ~~will~~ are ~~be~~ shown~~, in Figs. 1-32.~~ Each processor is discussed briefly below.

1.1 Fully Coherent Correlation of 200 cps Wide Linear FM Slide Signals of 2 Seconds Duration

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The processor used for these signals consists of a linear correlator with its reference matched to the signal, followed by a linear rectifier and an averager whose averaging time is equal

to the reciprocal of the input bandwidth. The modified ROC curves for this process are shown in Fig. 1. Since only a single Doppler channel output is provided with this processor, Doppler shifted returns will cause a slight degradation in its performance. For a given Doppler return, either positive or negative, a new set of modified ROC curves may be obtained from Fig. 1 by adding a small amount to the input signal-to-noise ratio which appears on each of the curves. The required increase in input signal-to-noise ratio may be obtained from Fig. 2 for Dopplers up to 12 knots. Figure 3 gives the rate of exceeding the threshold in the absence of signal as a function of the threshold setting, which is normalized in units of the noise standard deviation relative to the noise mean. Figure 5 gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate. This curve was obtained from Fig. 1 by the procedure mentioned above.

1.2 Fully Coherent Correlation of 200 cps Wide Ideal FM Slide Triplets of 2 Seconds Duration

The processor used here consists of a linear correlator which uses an ideal FM slide signal as a reference. This is followed by a linear rectifier and a perfect averager. The averaging time used here was 50 milliseconds in order to take advantage of the energy contained in all three of the signals in a triplet. The modified ROC curves for this process are shown in Fig. 6. The input signal-to-noise ratios shown are in terms of the total energy contained in all three of the triplet components. Figure 7 gives a plot of the threshold crossing rate vs the threshold setting for this processor. Due to the 50 millisecond time constant used, the output data rate is decreased and the statistics are more nearly Gaussian than in the previous process. Figure 8 was obtained from Fig. 6 and gives required input signal-to-noise ratio for 0.5 probability of detection vs. the threshold crossing rate.

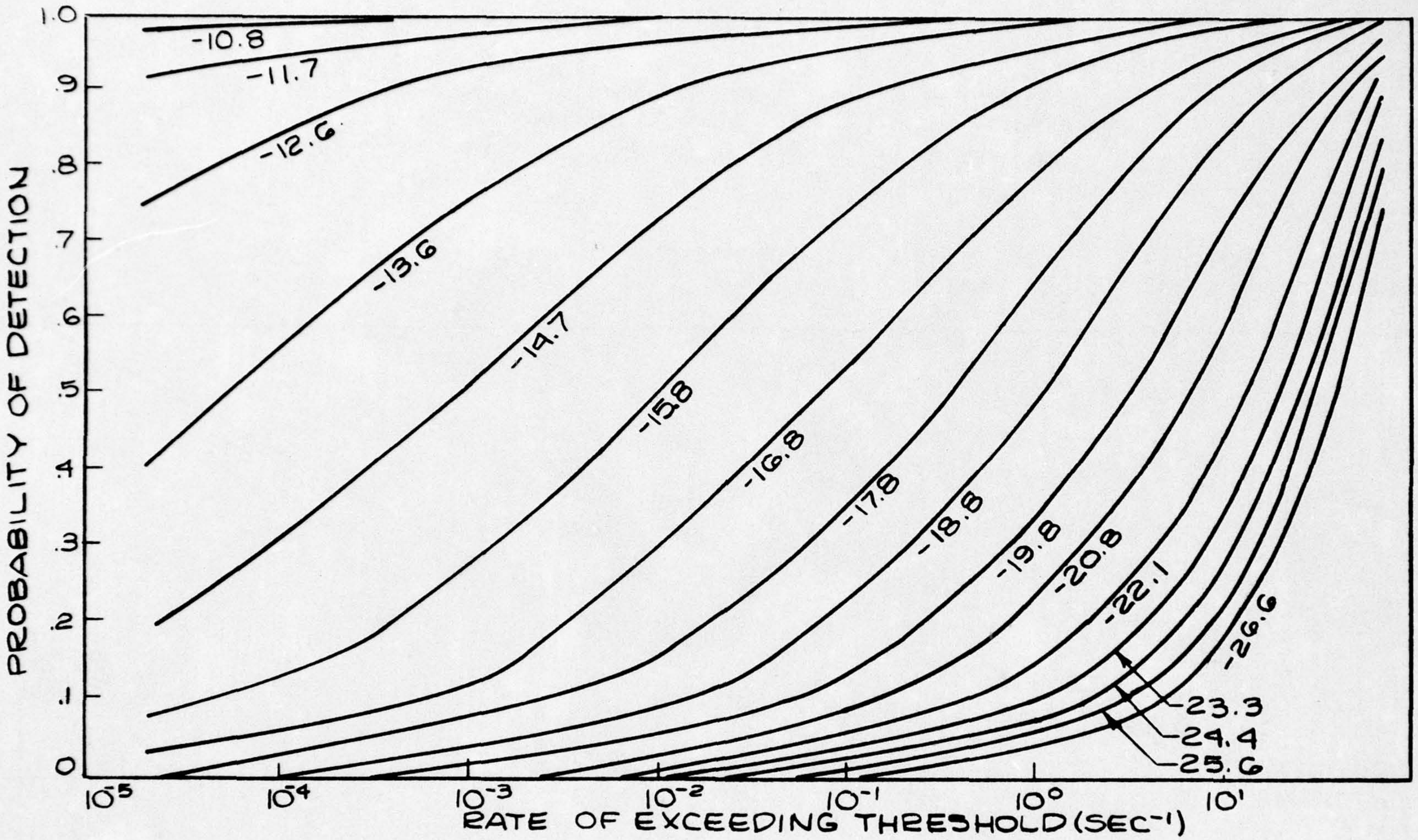

FIG. 1 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATION OF 200 CPS FM SLIDES OF 2 SEC DURATION. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

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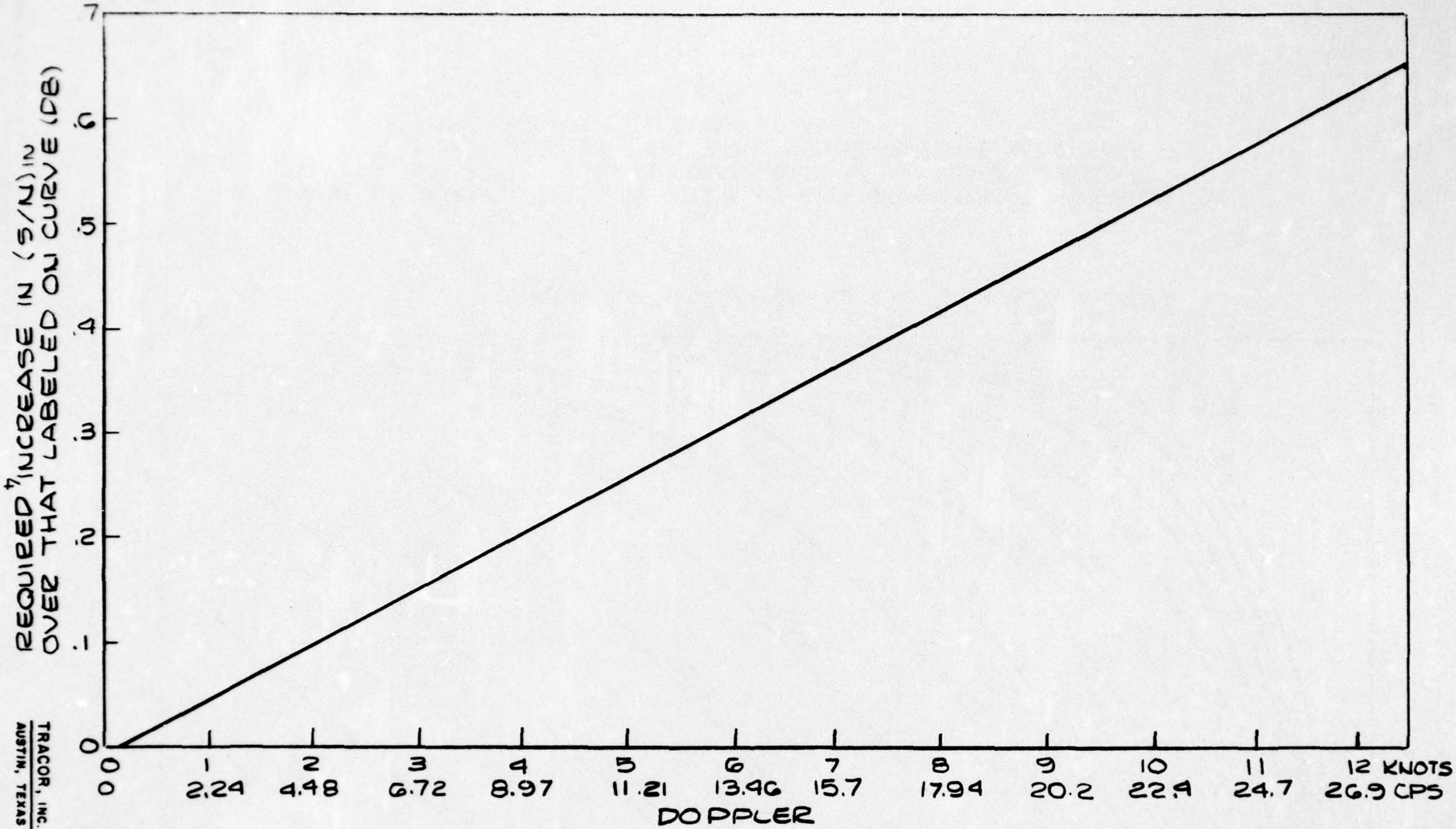

FIG. 2 REQUIRED INCREASE OF $(S/N)_{IN}$ AS A FUNCTION OF DOPPLER FOR 200 CPS FM SLIDE. A DOPPLER SCALE IN KNOTS IS SHOWN FOR 3.5 KC CENTER FREQUENCY.

TRACOR, INC. | DWG. A6-13-1988
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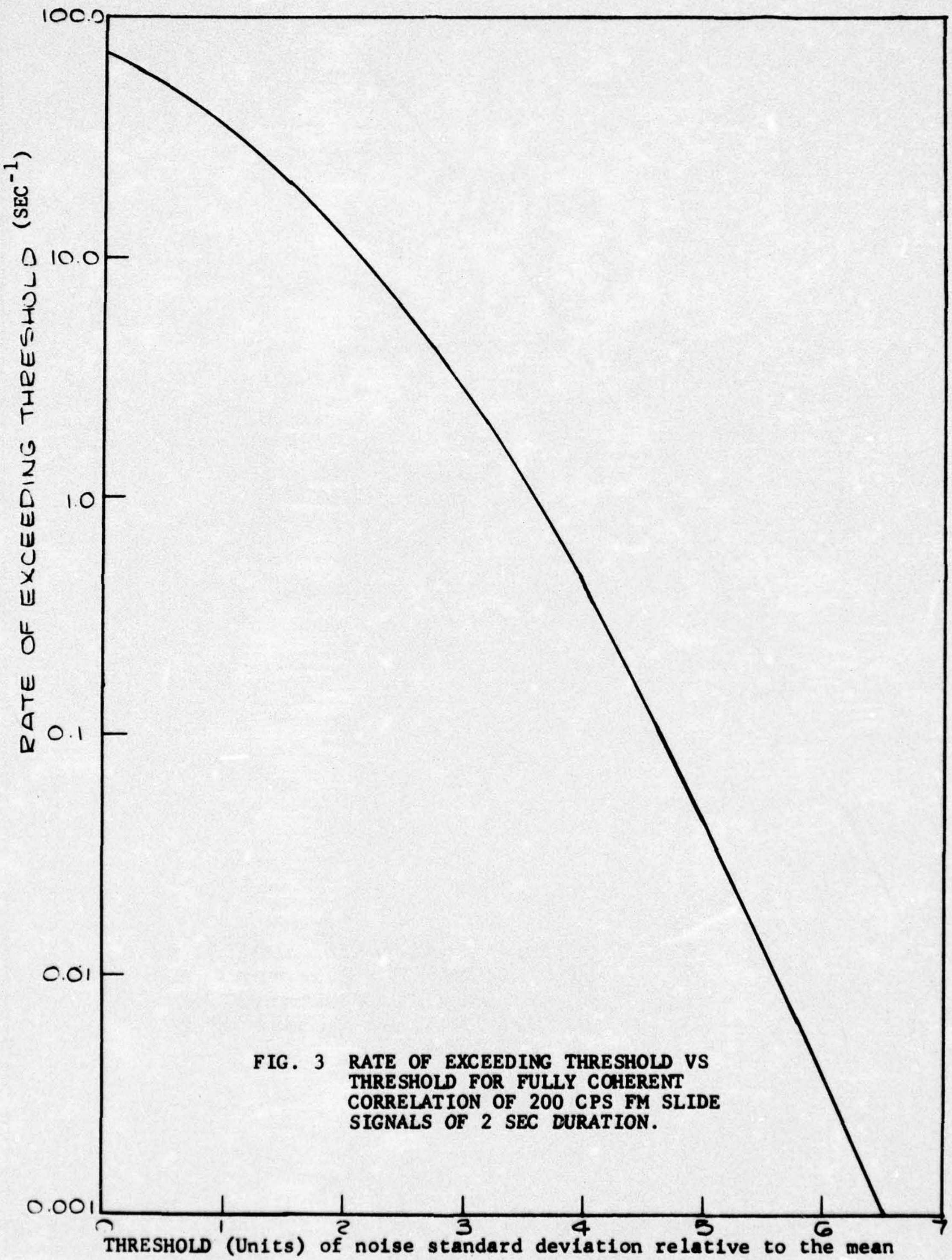

FIG. 3 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR FULLY COHERENT CORRELATION OF 200 CPS FM SLIDE SIGNALS OF 2 SEC DURATION.

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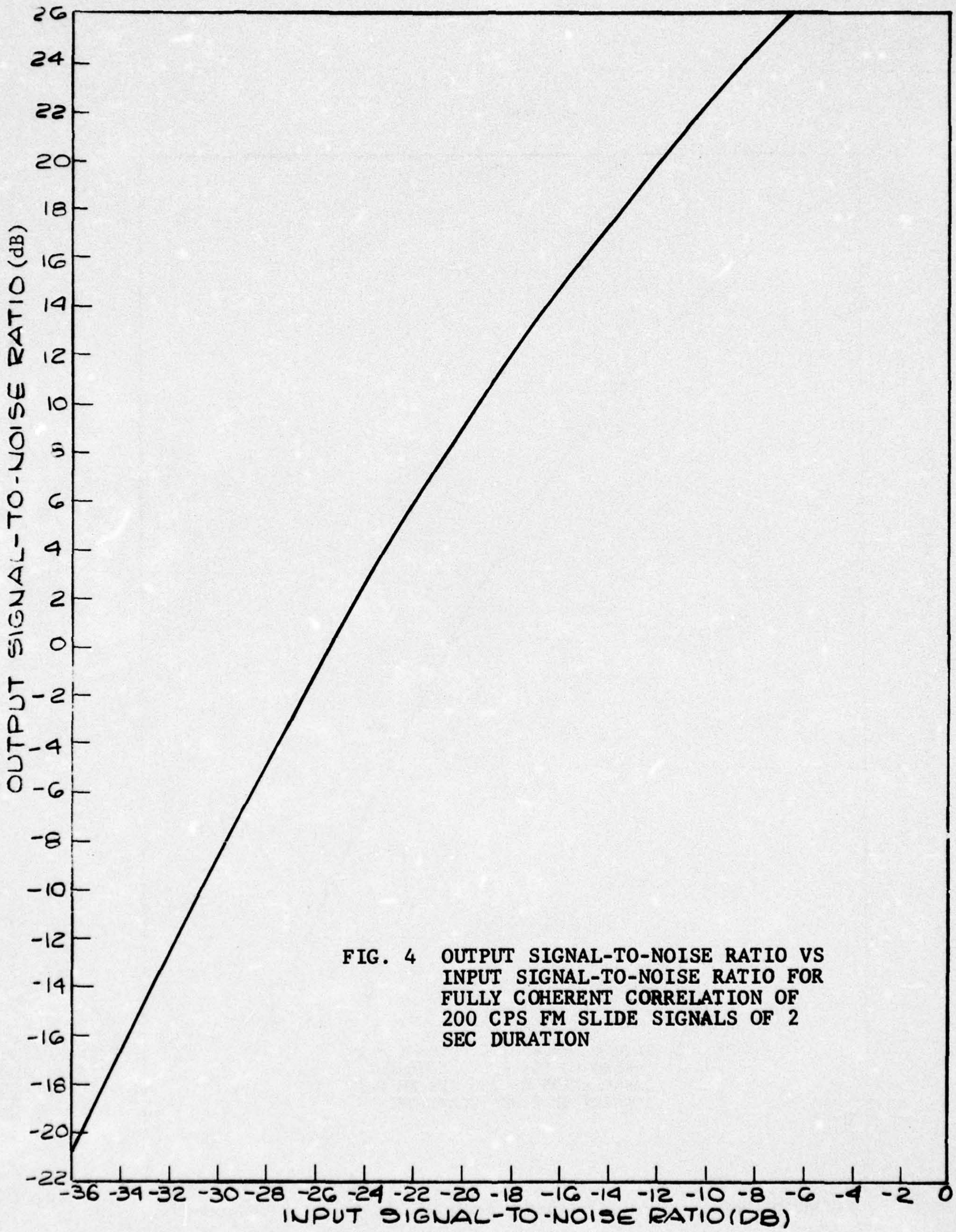

FIG. 4 OUTPUT SIGNAL-TO-NOISE RATIO VS INPUT SIGNAL-TO-NOISE RATIO FOR FULLY COHERENT CORRELATION OF 200 CPS FM SLIDE SIGNALS OF 2 SEC DURATION

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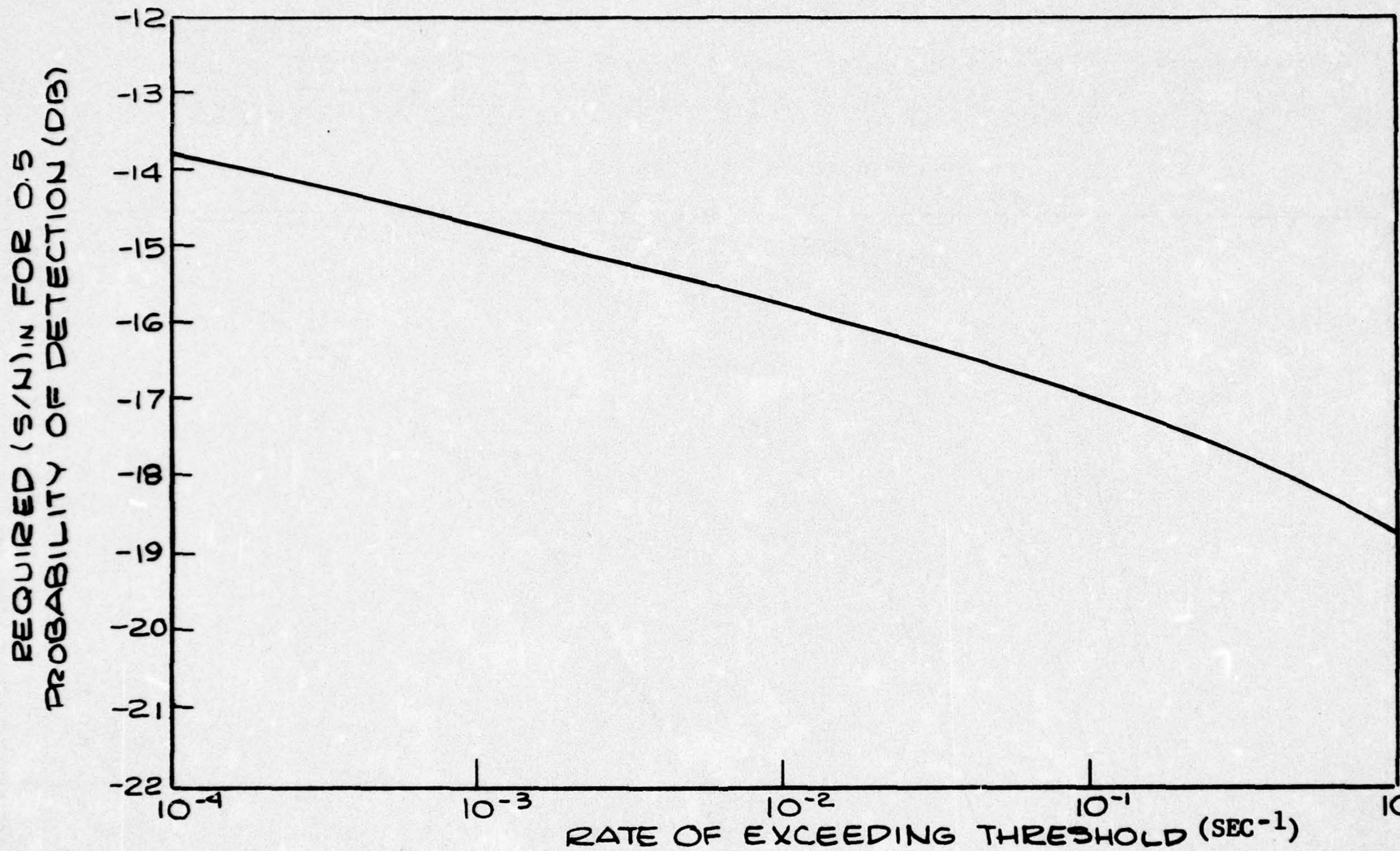

FIG. 5 REQUIRED $(S/N)_{IN}$ FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATION OF 2 SEC, 200 CPS FM SLIDE.

TRACOR, INC. | DWG. A6-13-1989
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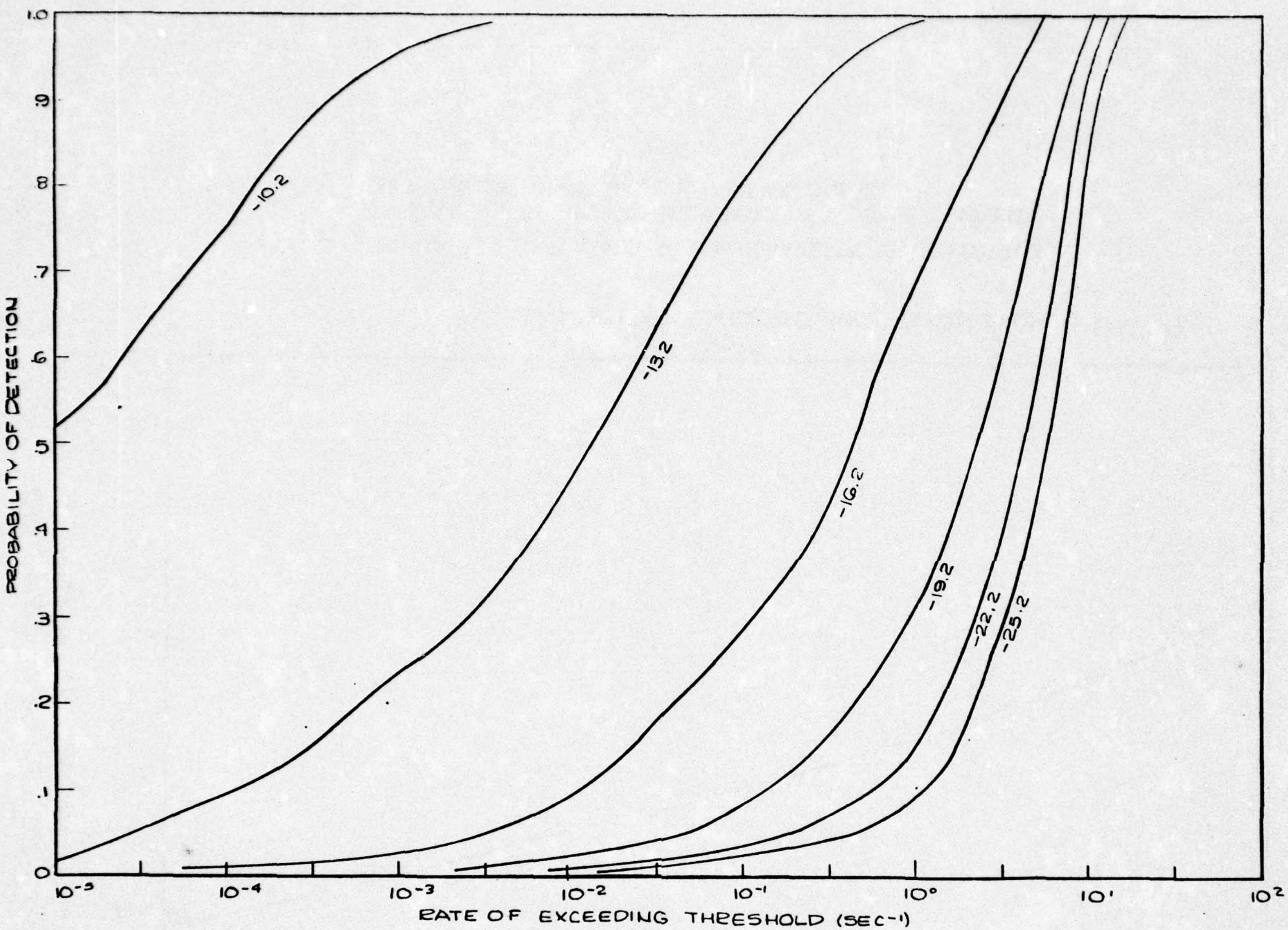

FIG. 6 - PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATION OF 2 SEC, 200 CPS FM TRIPLETS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG. A6-13-1974
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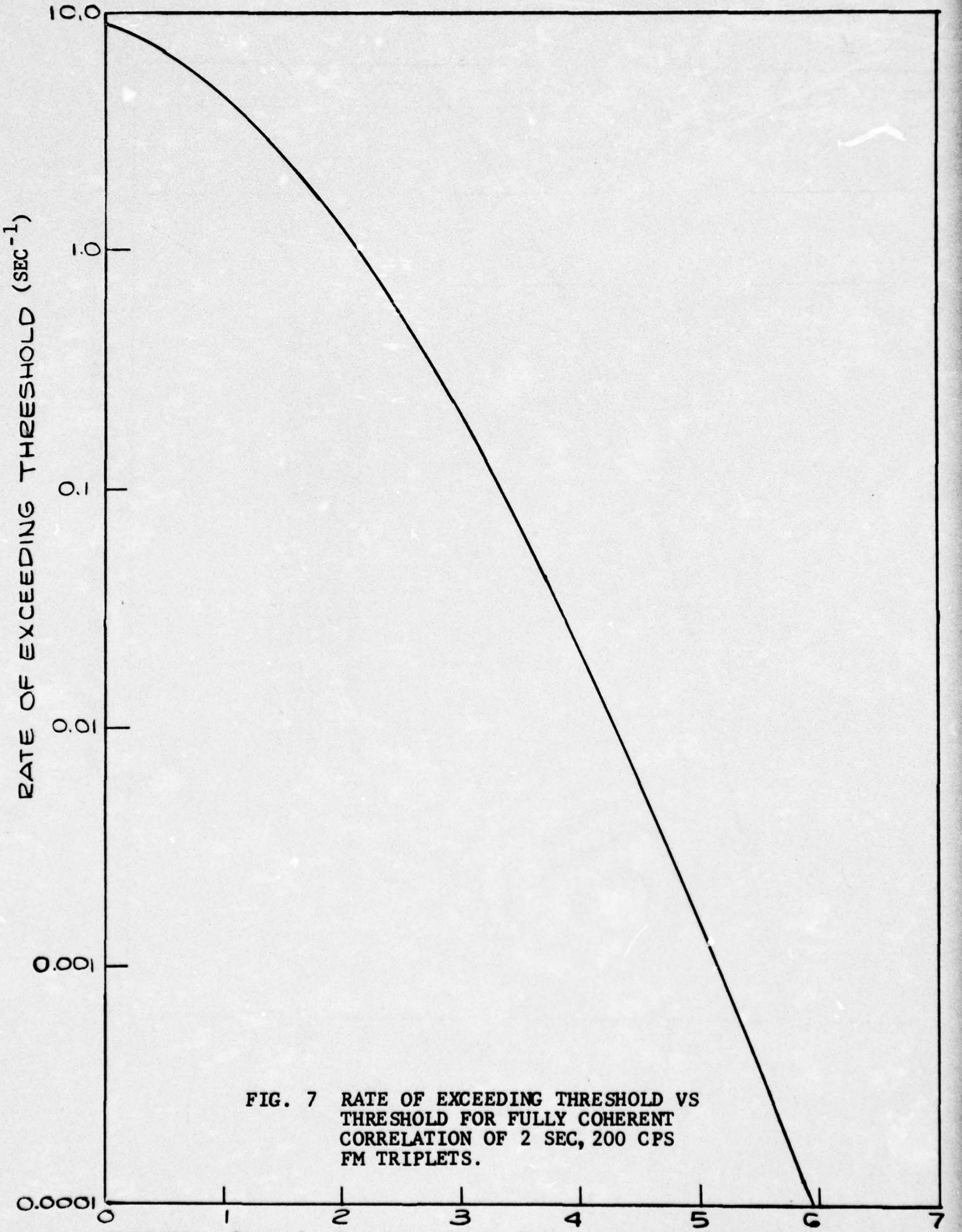

FIG. 7 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR FULLY COHERENT CORRELATION OF 2 SEC, 200 CPS FM TRIPLETS.

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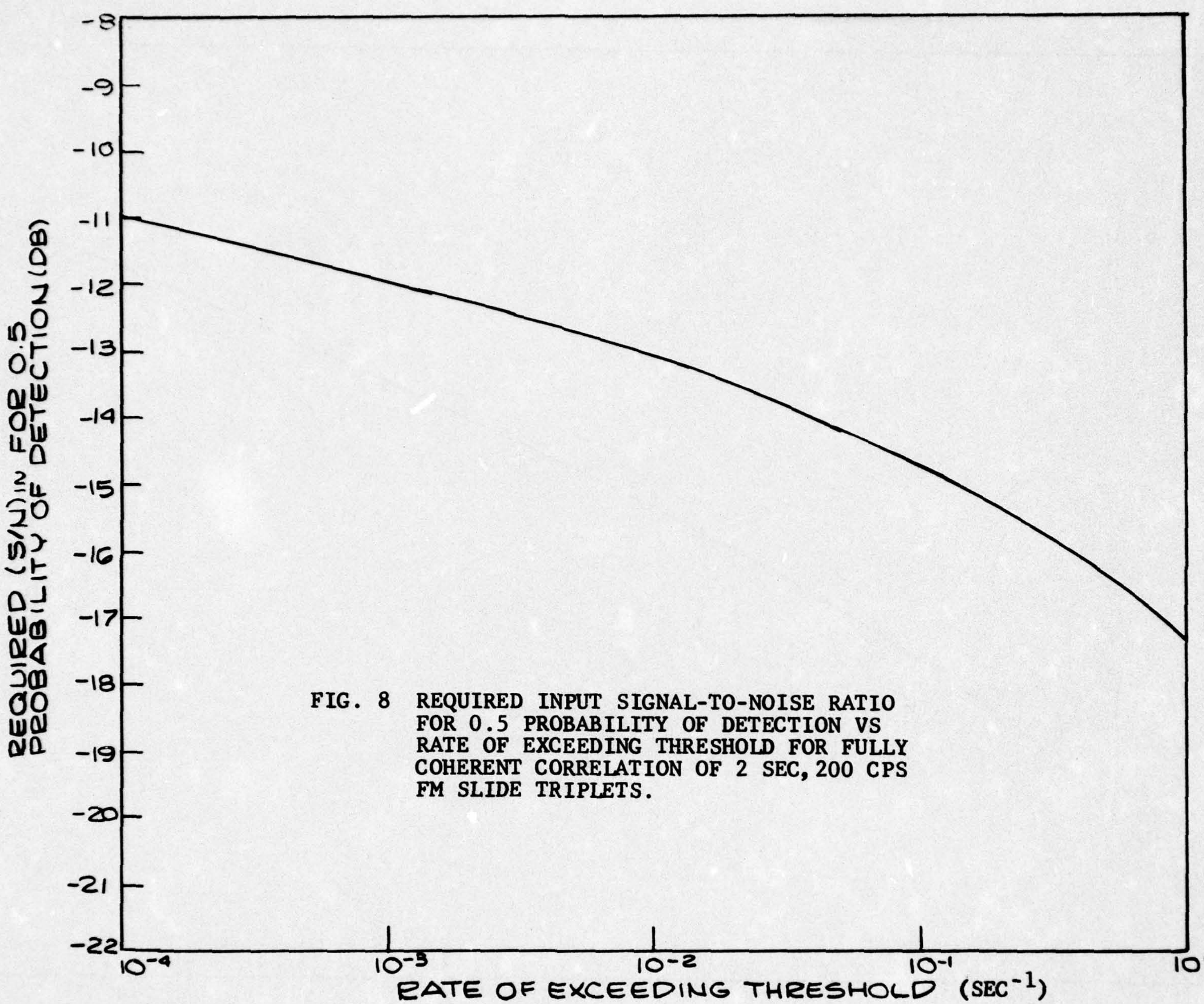

FIG. 8 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATION OF 2 SEC, 200 CPS FM SLIDE TRIPLETS.

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1.3 Correlation by Partial Sums of 200 cps Linear FM Slide Signals of 2 Seconds Duration

Correlation by partial sums uses two or more correlators, each having a reference that corresponds to part of the signal. For two-piece partial sums correlation, for example, two correlators are used. Each of these correlators uses one-half the signal as a reference. For this example, one correlator contained a reference which consisted of a 1 second long 100 cycles per second FM slide running from 200 to 300 cycles per second. The other correlator used a reference which was 1 second long and consisted of a 100 cycle per second FM slide running from 300 to 400 cycles per second. The output of each of these correlators was rectified and averaged for 10 milliseconds. When a signal is correlated a peak occurs from the first correlator one second before the peak from the second correlator. The first peak is delayed by one second such that the two peaks line up and the two channels are then cross added. Modified ROC curves are shown for this process in Fig. 9. Figure 10 is obtained from Fig. 9 and gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate. Figure 11 gives the rate of exceeding threshold as a function of the threshold setting for this process.

1.4 Correlation by Partial Sums of 2 Second, 200 cps FM Triplets

This process is carried out in a manner similar to that for ideal signals. The correlator references here are copies of a single component of the triplets. The averaging time used in this process is 50 milliseconds for each correlator. Figure 12 gives the modified ROC curves for this process and

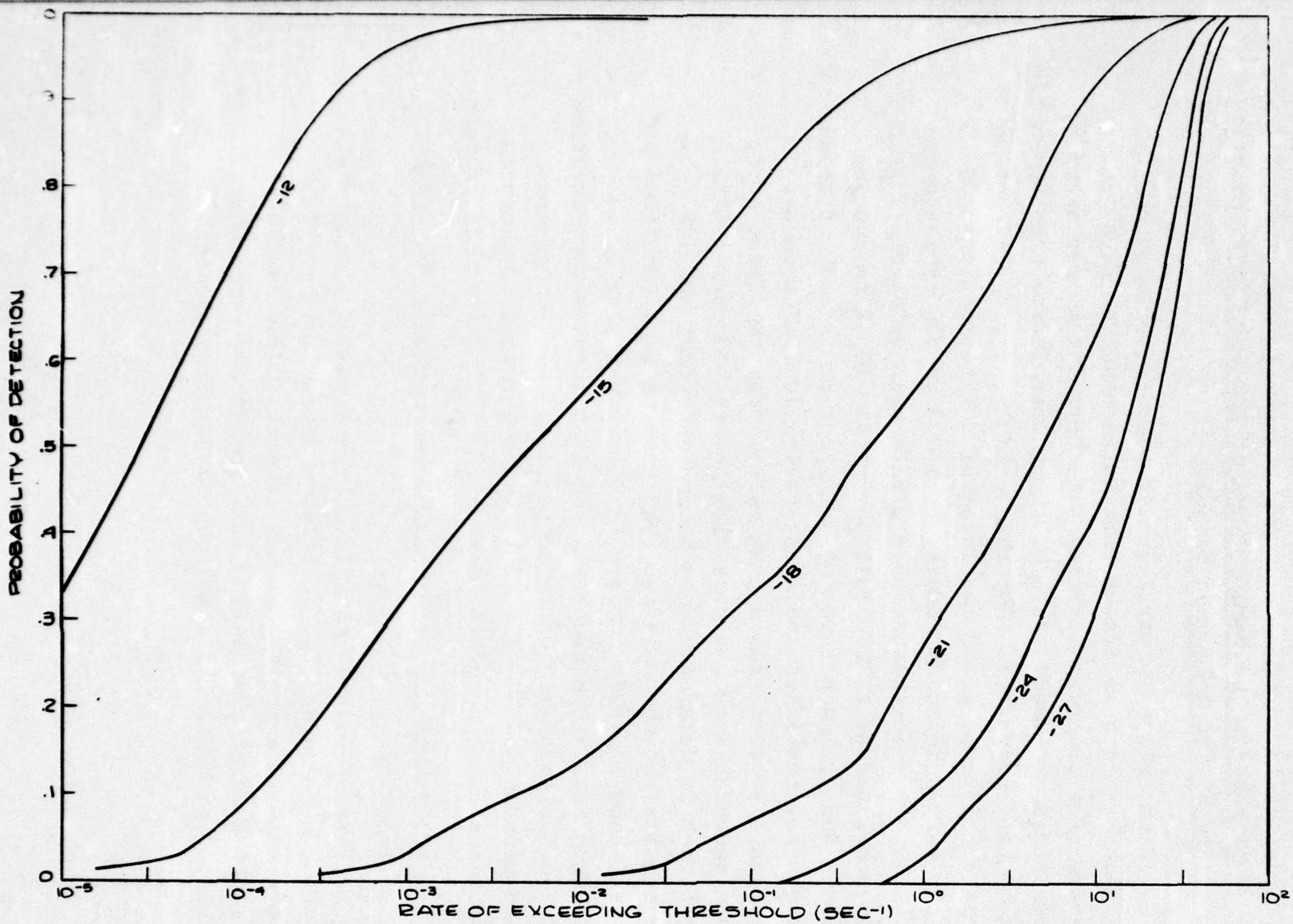

FIG. 9 - PROBABILITY OF DETECTION VS. RATE OF EXCEEDING THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 200 CPS FM SLIDES OF 2 SEC. DURATION. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

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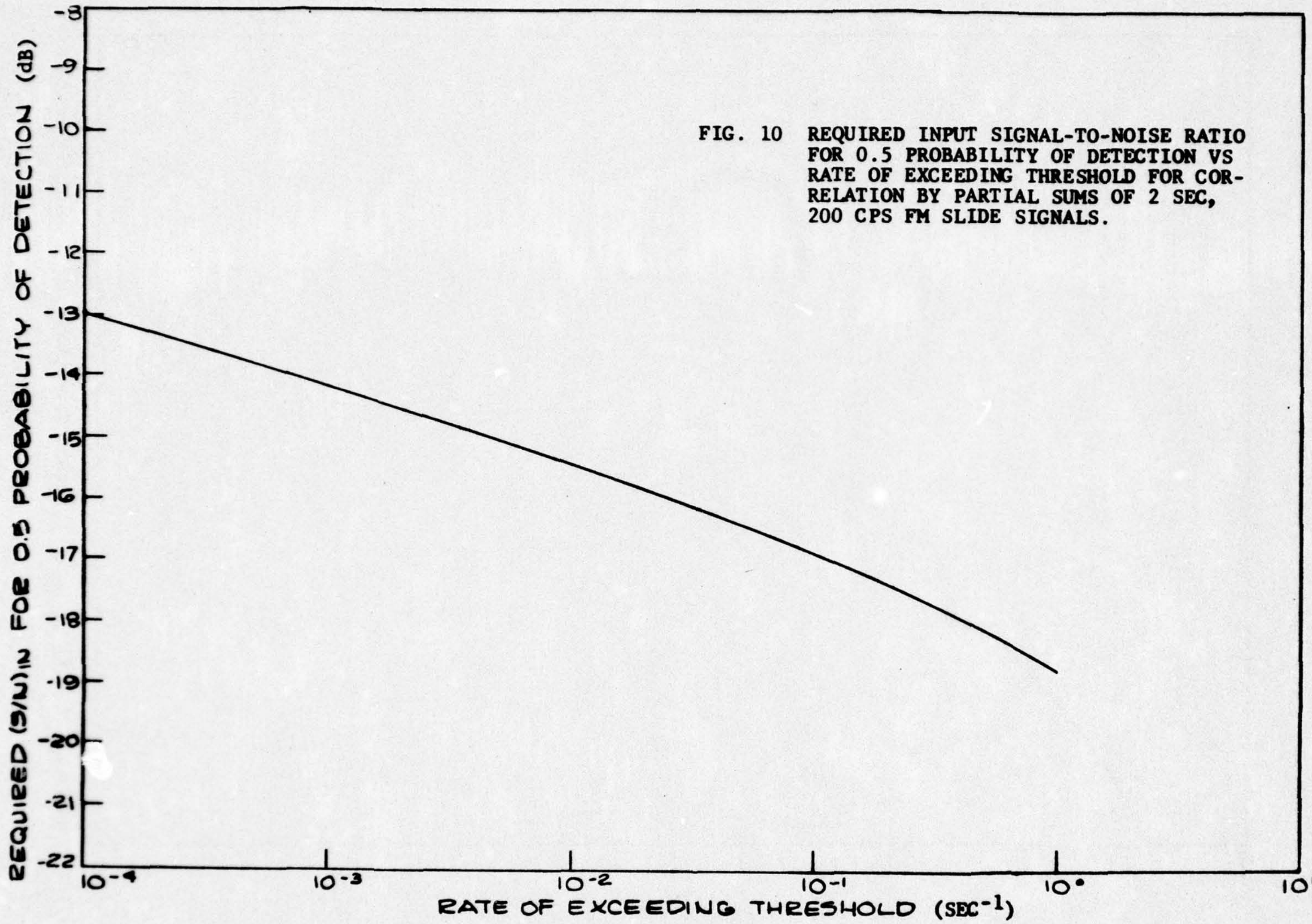

FIG. 10 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 2 SEC, 200 CPS FM SLIDE SIGNALS.

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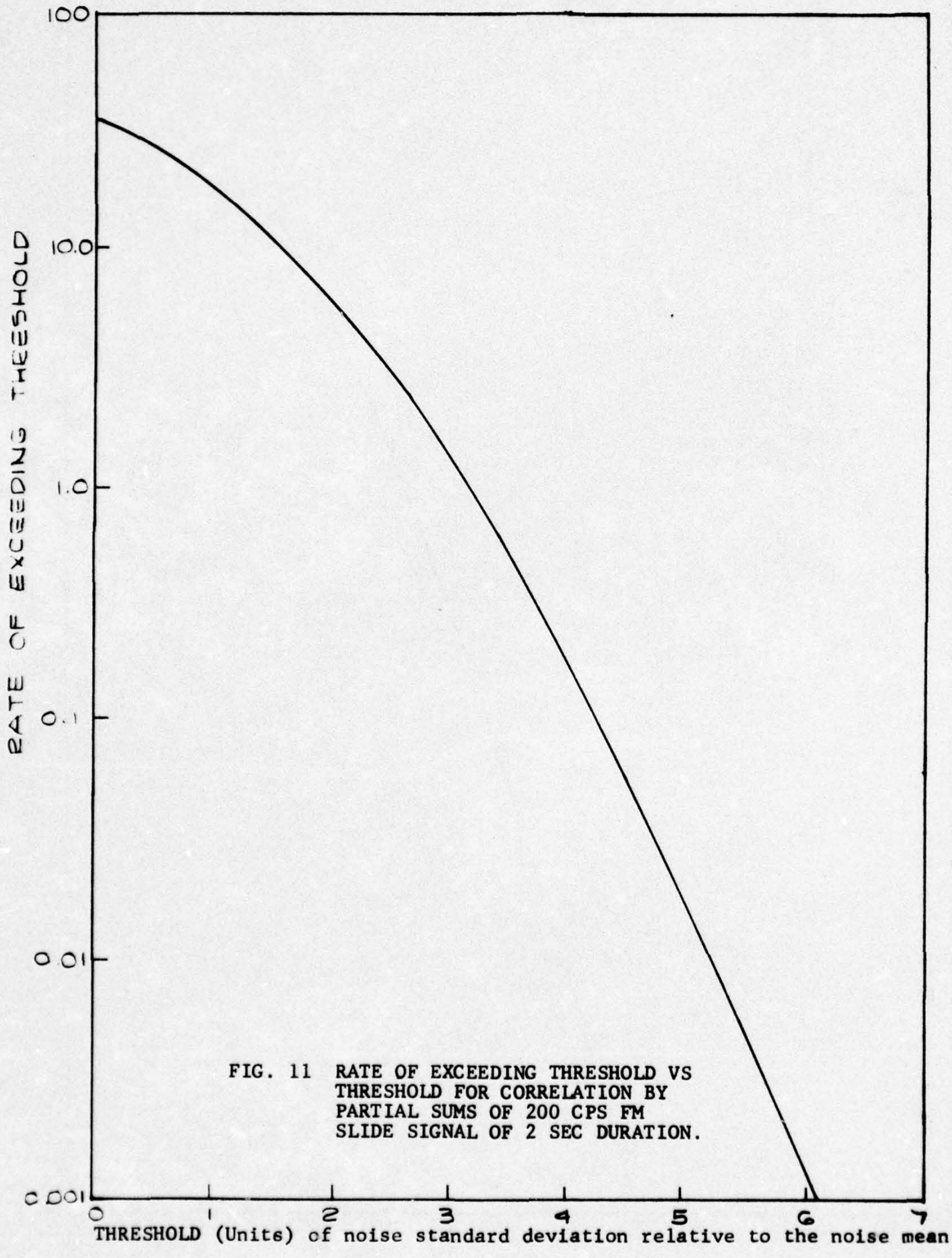

FIG. 11 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 200 CPS FM SLIDE SIGNAL OF 2 SEC DURATION.

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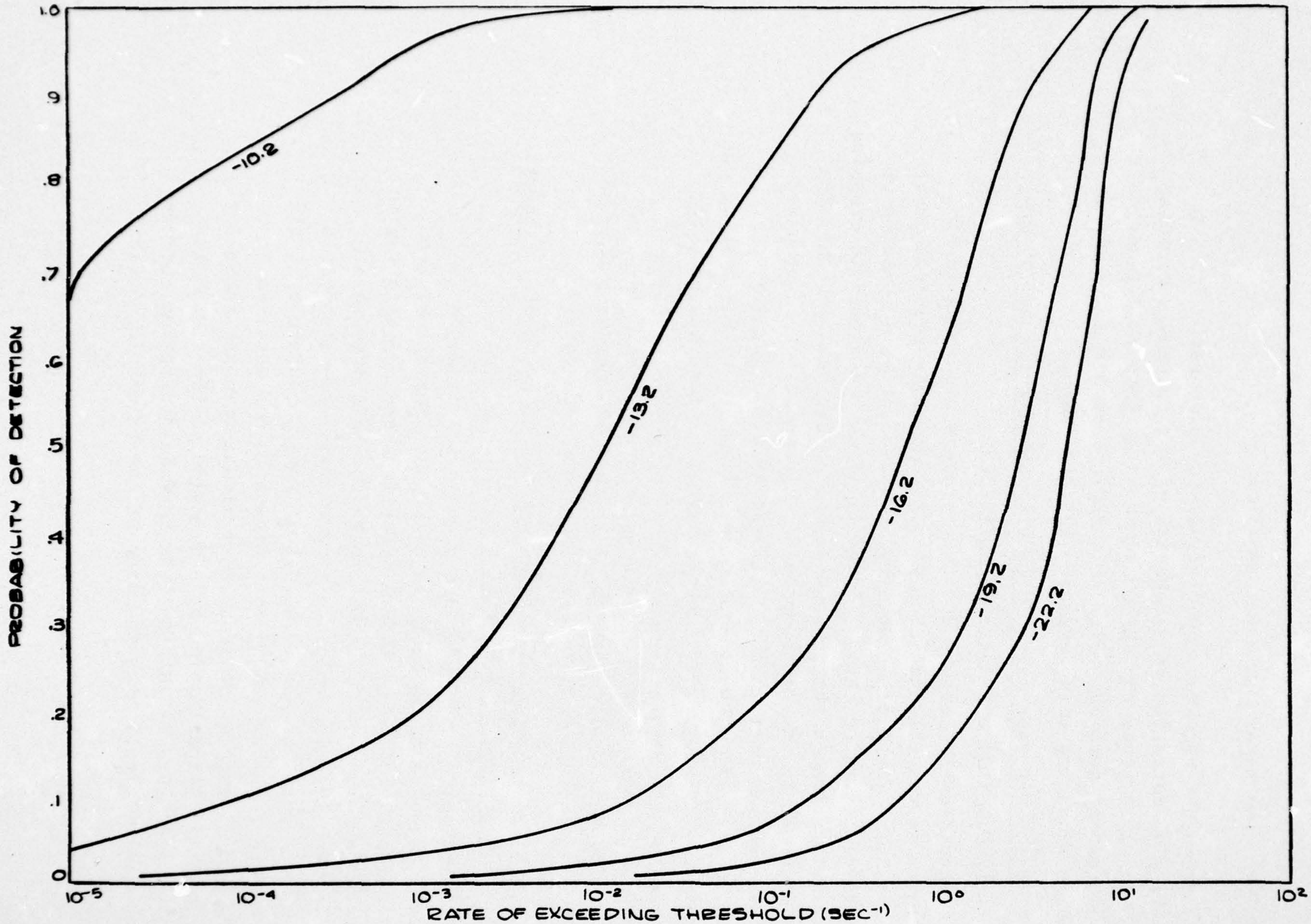

FIG. 12 - PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 2 SEC, 200 CPS FM TRIPLETS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG. A6-13-1975
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Fig. 13 gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate. Figure 14 gives the threshold crossing rate as a function of the threshold setting. Figure 14 differs from Fig. 11 due to the longer averaging times employed in this example.

1.5 Fully Coherent Correlation with OR Circuits of 200 cps PRFM Signals of 2 Seconds Duration

Modified ROC curves for this process are shown in Fig. 15. Figure 16 was obtained from Fig. 15 and gives required input signal-to-noise for 0.5 probability of detection as a function of the threshold crossing rate. Figure 17 gives the threshold crossing rate as a function of the threshold setting for this process. The main difference in the performance of this processor as compared to fully coherent correlation of linear FM slide signals is evident in Fig. 17. The threshold crossing rate in the absence of signal from this processor is considerably higher than that for the linear FM processor. This is due to the fact that the 2 second PRFM signal has a ½ cycle Doppler resolution. Thus, in order to cover a Doppler range of ± 25 cps, 100 channels must be used with a proportional increase in output data rate.

1.6 Fully Coherent Correlation with OR Circuits of 2 Seconds, 200 cps Ideal PRFM Triplets

The correlator reference used in this example is identical to one component of the triplets. The output from the linear correlator is linearly rectified and averaged for 50 milliseconds. The modified ROC curves for this process are shown in Fig. 18. The values of input signal-to-noise ratio shown are in terms of the total signal energy contained in all three of the triplet components. Figure 19 was obtained from Fig. 18 and gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate. Figure 20 gives the threshold crossing rate in the absence of signal as a function of the threshold setting.

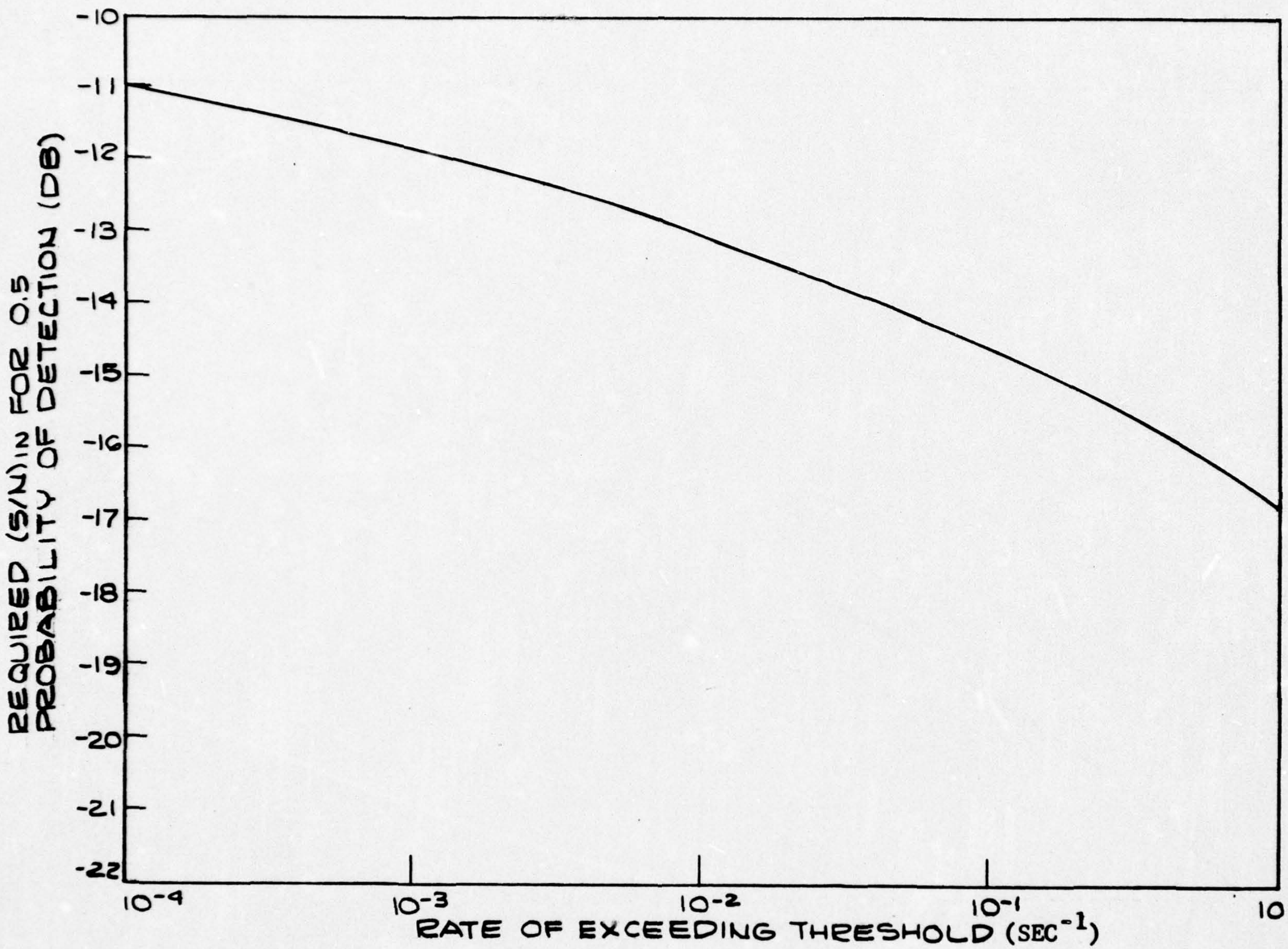

FIG. 13 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 2 SEC, 200 CPS FM SLIDE TRIPLETS.

TRACOR, INC. | DWG. A6-13-1994
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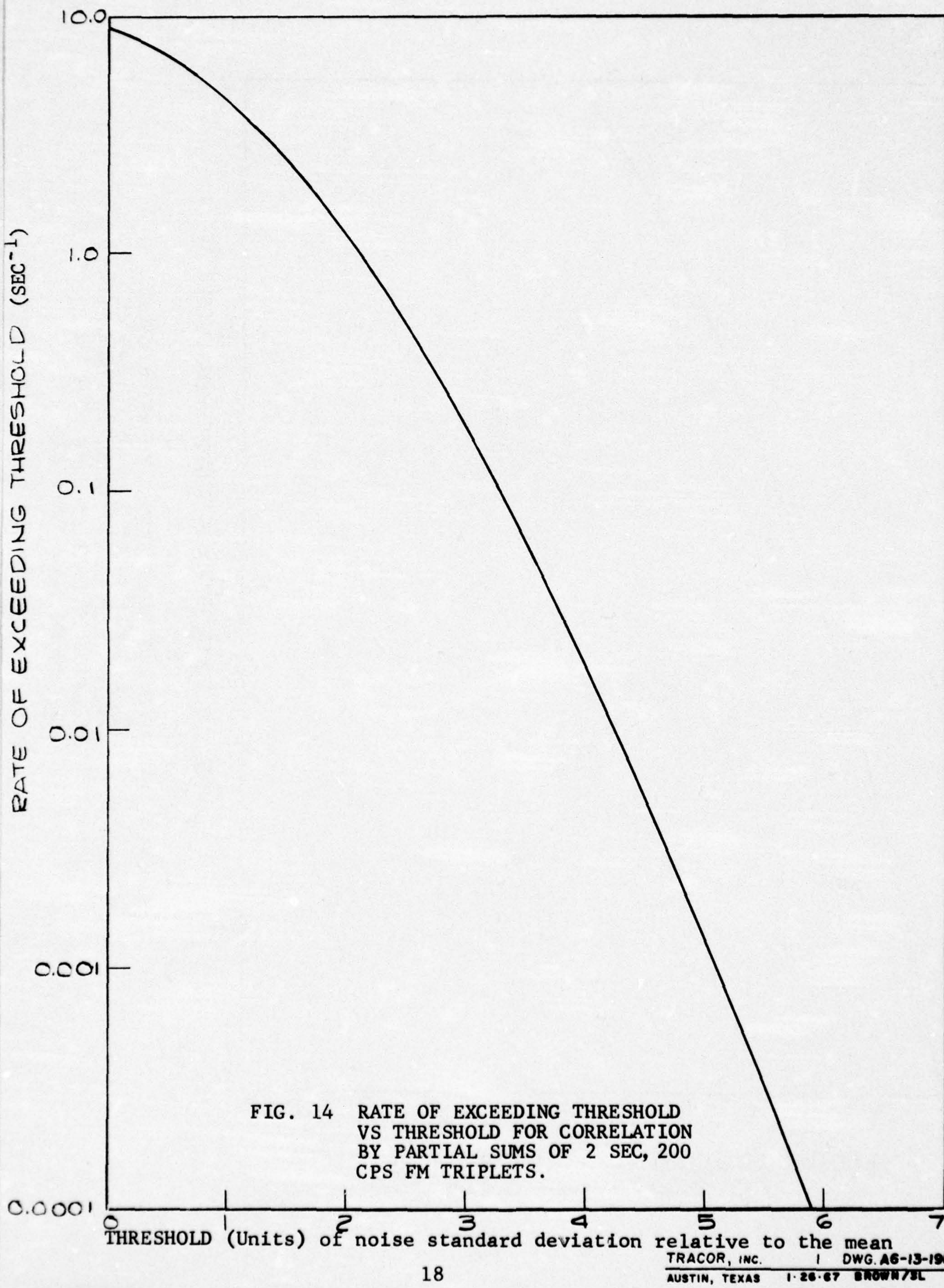

FIG. 14 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 2 SEC, 200 CPS FM TRIPLETS.

TRACOR, INC. 1 DWG. A6-13-1984
AUSTIN, TEXAS 1-26-67 BROWN/SL

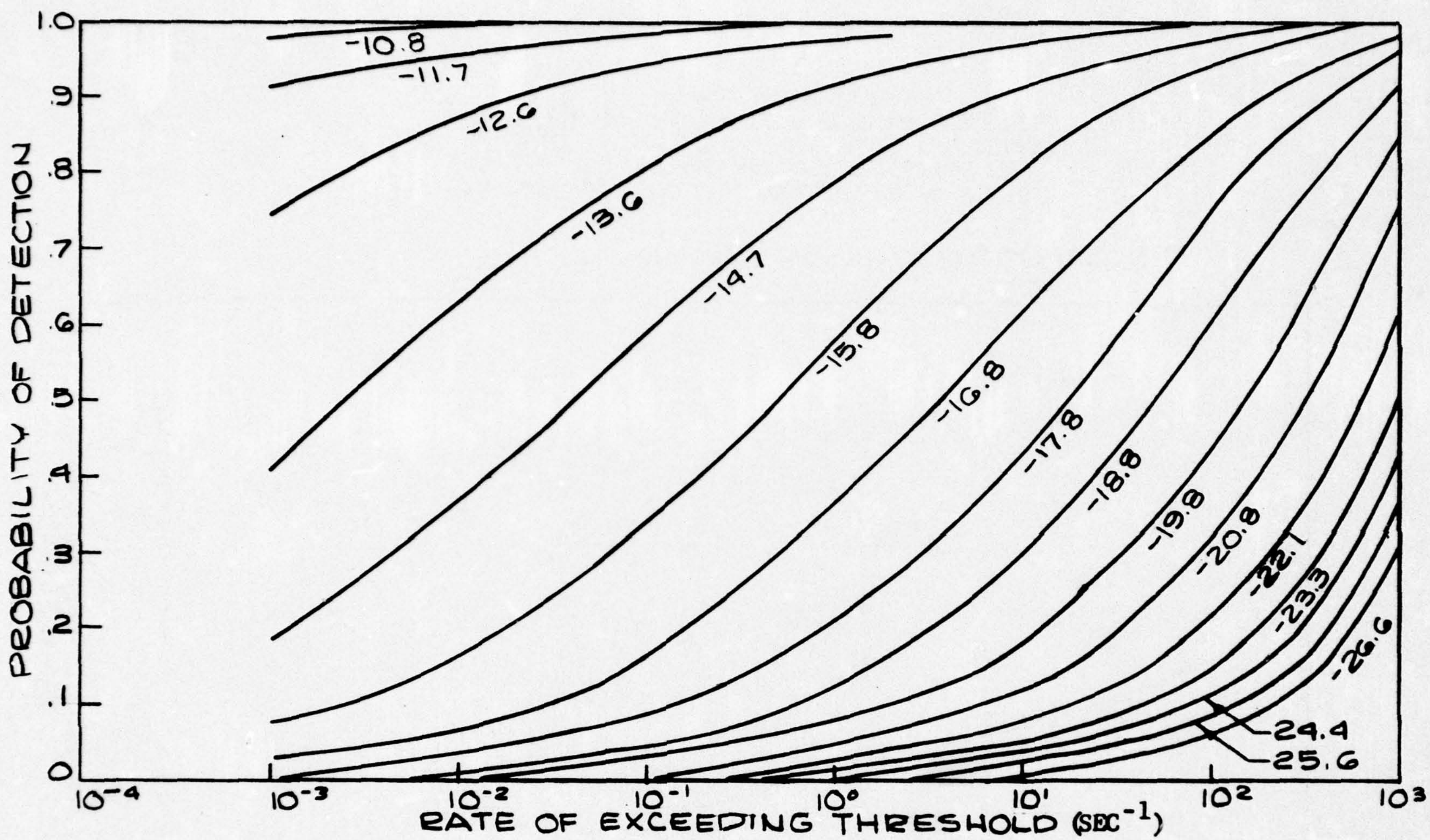

FIG. 15 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATION WITH OR CIRCUITS OF 200 CPS PRFM SIGNALS OF 2 SEC DURATION. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. | DWG. A6-13-1973
AUSTIN, TEXAS 1-26-67 BROWN/SL

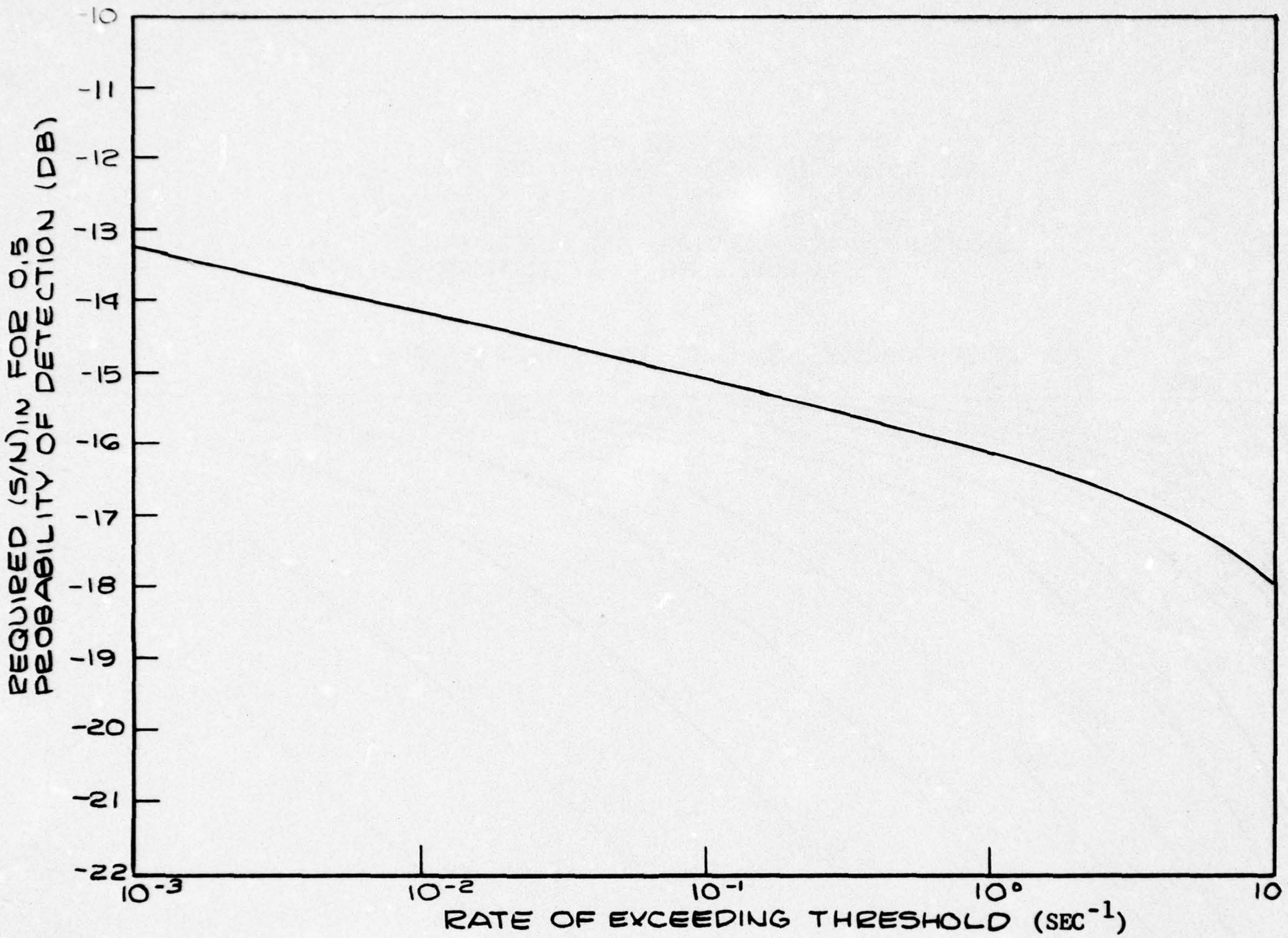

FIG. 16 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATION WITH OR CIRCUITS OF 2 SEC, 200 CPS PRFM SIGNALS.

TRACOR, INC. | DWG. A6-13-1995
AUSTIN, TEXAS 1-26-67 BROWN/SL

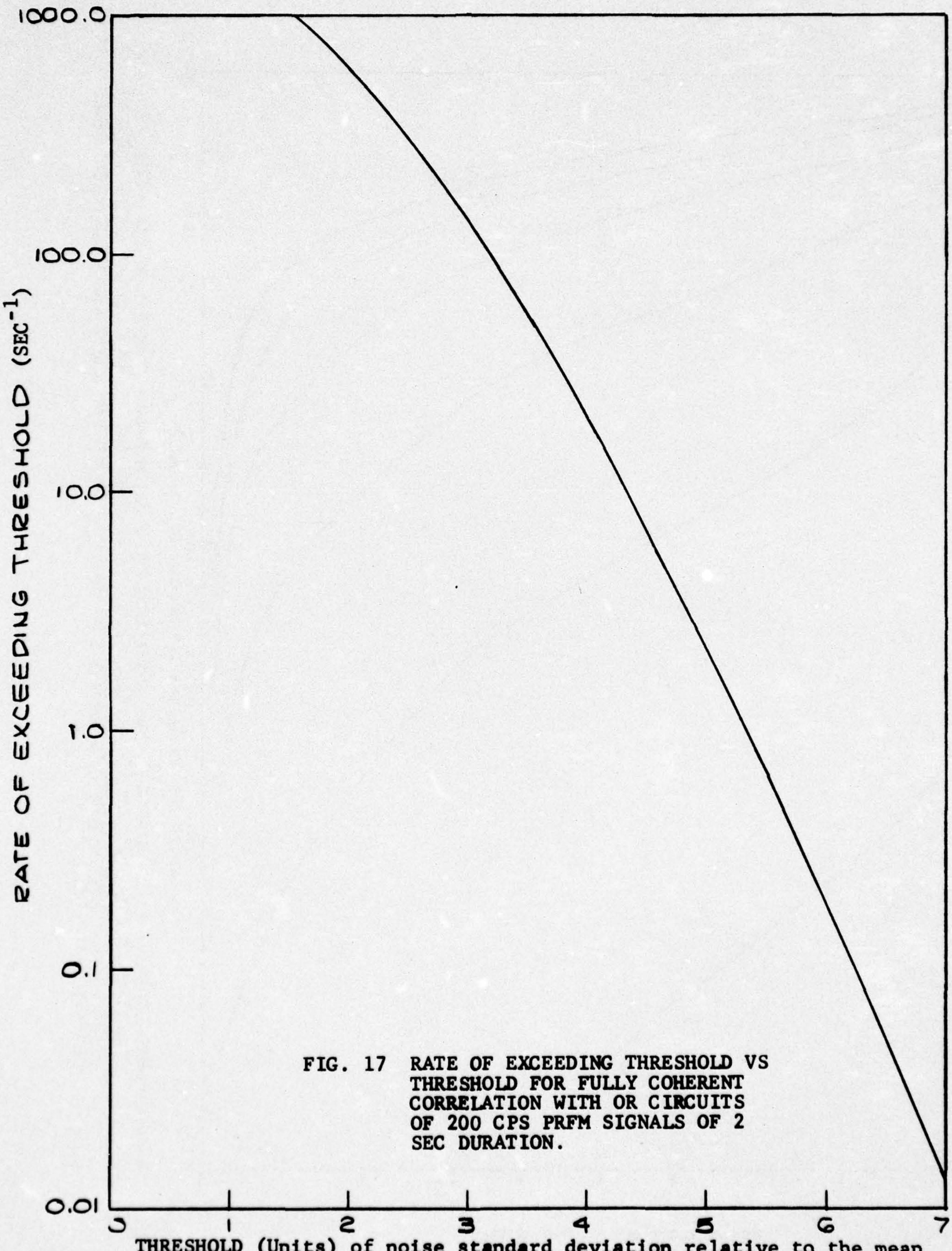

FIG. 17 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR FULLY COHERENT CORRELATION WITH OR CIRCUITS OF 200 CPS PRFM SIGNALS OF 2 SEC DURATION.

TRACOR, INC. | DWG. A6-13-1983
AUSTIN, TEXAS 1-26-67 BROWN/SL

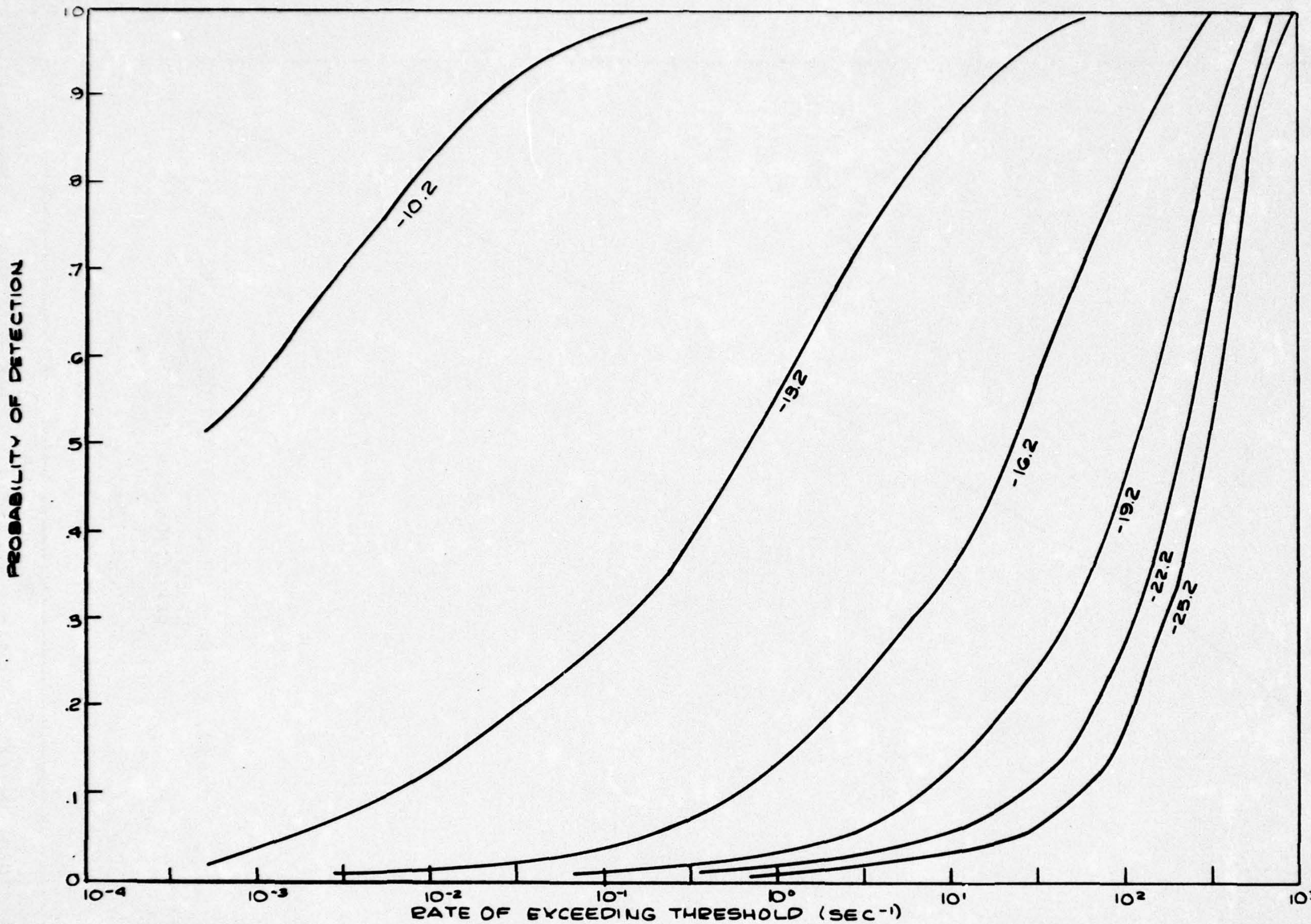

FIG 18- PROBABILITY OF DETECTION VS. RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATON WITH OR CIRCUITS OF 2 SEC, 200 CPS PRFM TRIPLETS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG. A6-13-1971
AUSTIN, TEXAS 1-26-67 BROWN/SL

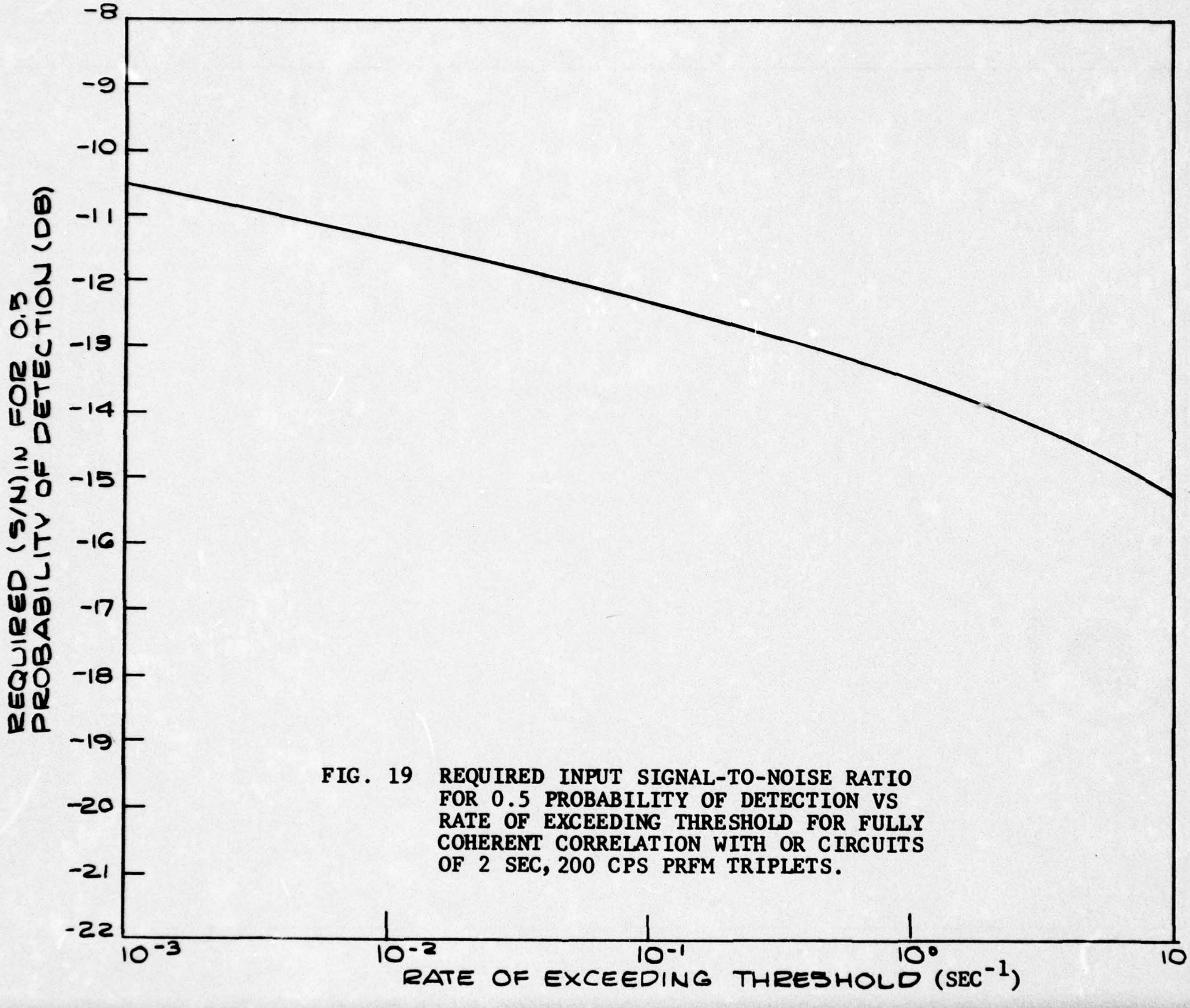

FIG. 19 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULLY COHERENT CORRELATION WITH OR CIRCUITS OF 2 SEC, 200 CPS PRFM TRIPLETS.

TRACOR, INC. | DWG. A6-13-199
AUSTIN, TEXAS 1-20-67 BROWN/SL

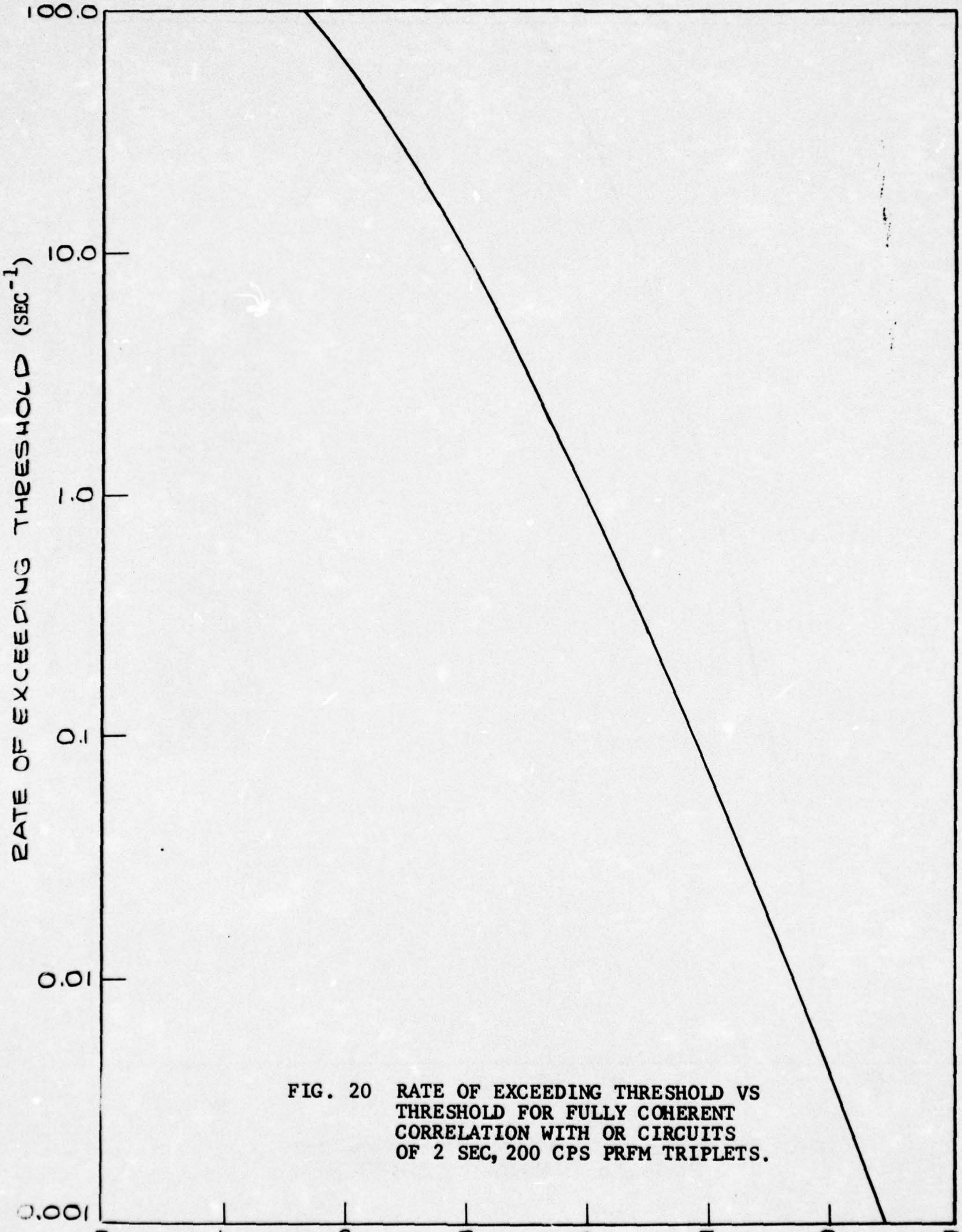

FIG. 20 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR FULLY COHERENT CORRELATION WITH OR CIRCUITS OF 2 SEC, 200 CPS PRFM TRIPLETS.

TRACOR, INC. | DWG. A6-13-1906
AUSTIN, TEXAS 1-26-67 BROWN/BL

This differs from Fig. 17 due to the increased averaging time.

1.7 Ideal 200 cps, 2 Second DRTFM Signals Processed as in a Diagram Furnished by USNUSL

The DRTFM signals consist of a linear FM slide signal of 1 second duration running from 200 to 300 cycles per second followed immediately by a 1 second linear FM slide signal running from 400 cycles per second to 300 cycles per second. These signals were processed in a manner described in a diagram which was enclosed with USNUSL letter Serial Number 935.1-0287. A simplified description of this processor follows: The up slide and the down slide are first processed separately using linear, quadrature correlators. A reference is extracted from one of the resulting channels to be replica correlated against the second channel. A periodic updating of the data in both channels is carried out such that during one period of time the entire signal structure from the first channel is contained in the reference which is replica correlated against the second channel. The time at which the peak of this correlation is obtained is then used to align the signals in the two channels such that they may be summed up. Detection is obtained when the peak from the last correlator exceeds a threshold, but for a detection to be valid a certain accuracy in aligning the two channels must be achieved. For ideal signals, at least, this processor would provide a direct measure of Doppler. Simulations were made using three values of alignment accuracy of the two channels. Figure 21 shows modified ROC curves for this processor using an alignment accuracy of ± 5 milliseconds. Figure 22 shows modified ROC curves for the processor with an alignment accuracy within ± 10 milliseconds, and Fig. 23 shows modified ROC curves for alignment accuracies within ± 20 milliseconds. The processor performance drops considerably in the small signal region when a high degree of alignment accuracey is required. Figure 24 gives the required input signal-to-noise ratio for 0.5 probability

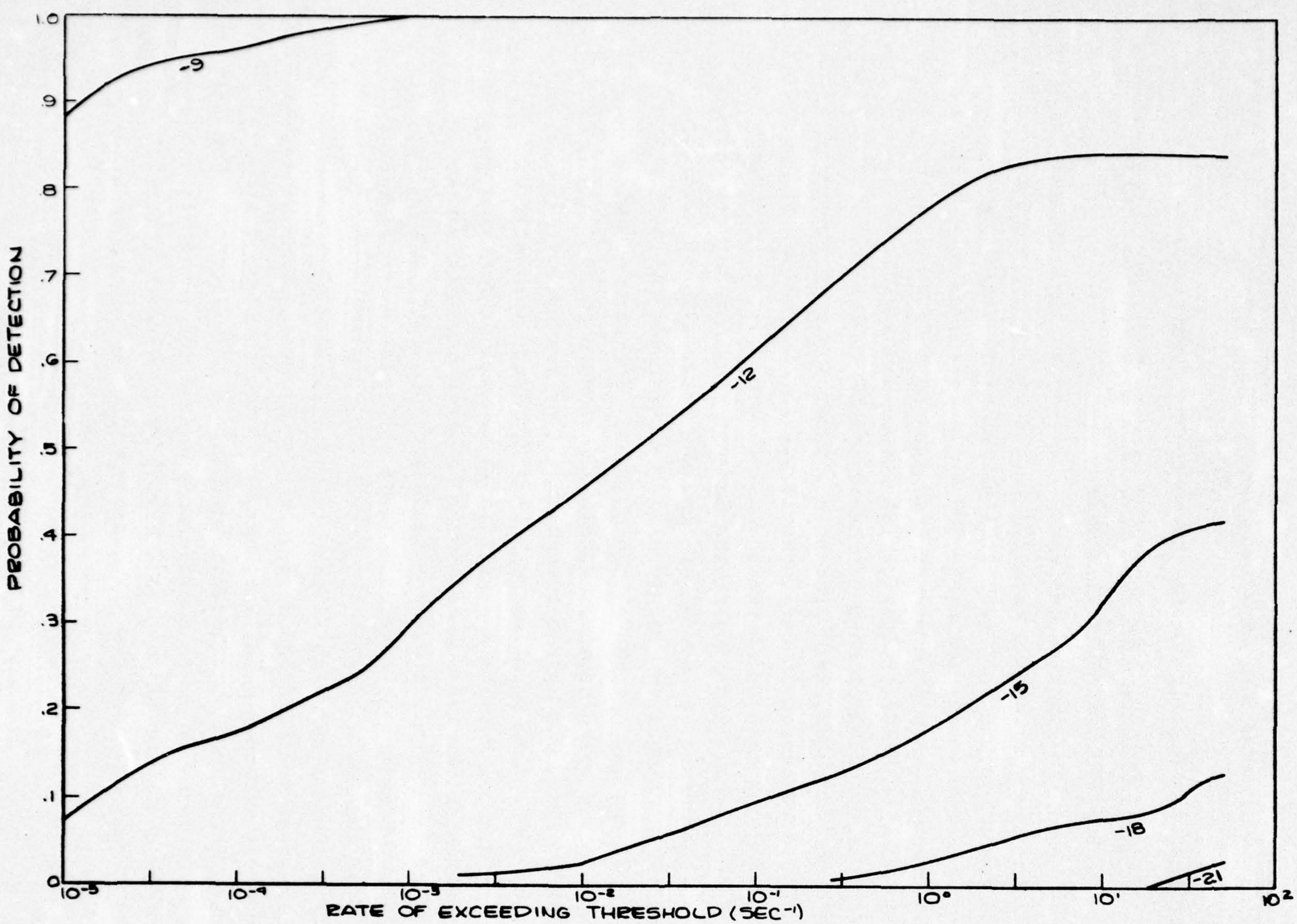

FIG. 21 - PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC. DRTFM SIGNALS PROCESSED AS IN DIAGRAM FROM USN USL. ALIGNMENT ACCURACY ±5 MS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG. A6-13-1979
AUSTIN, TEXAS 1·26·67 BROWN/SL

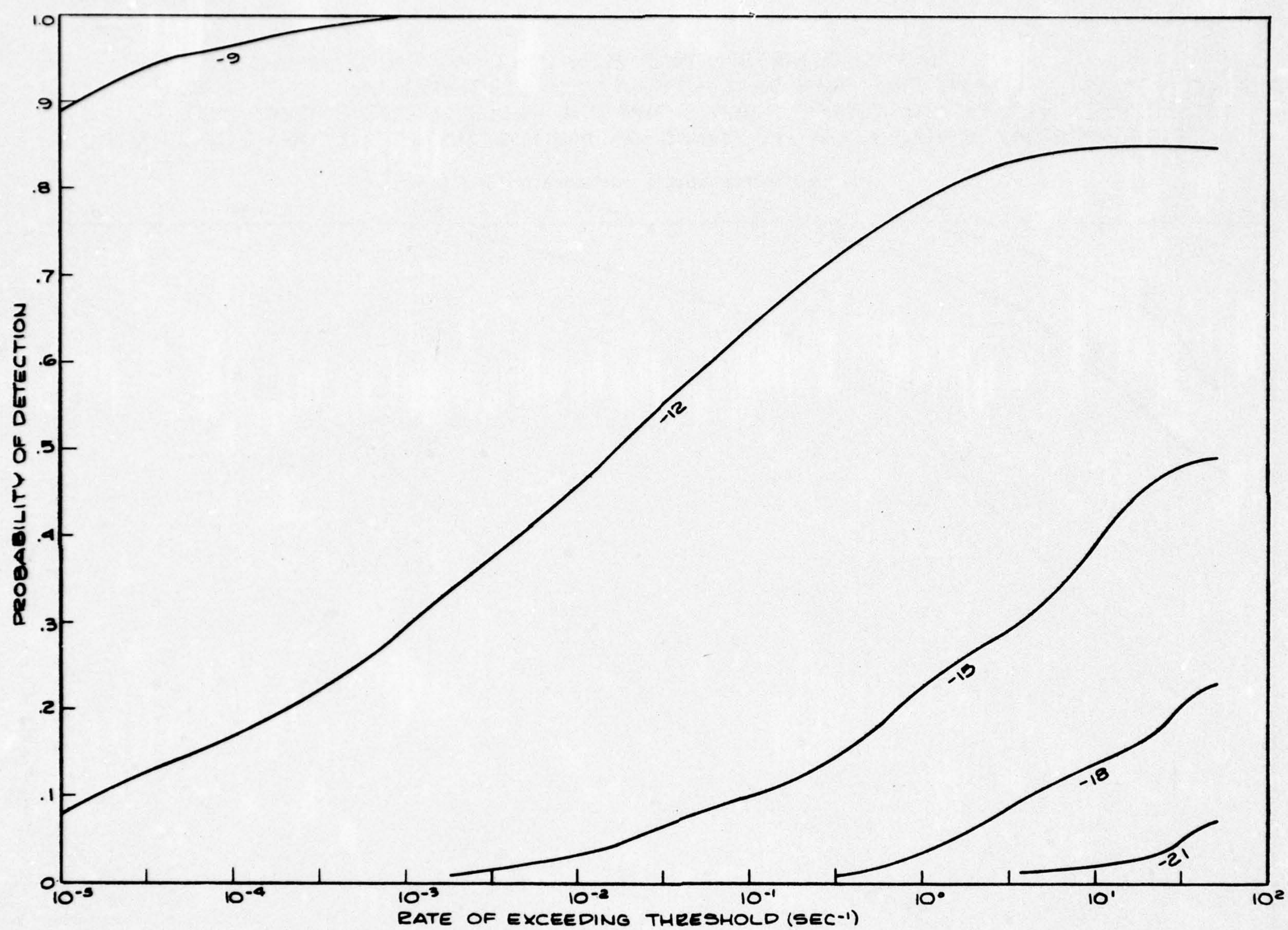

FIG. 22 - PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC. DRTFM SIGNALS PROCESSED AS IN DIAGRAM FROM USN USL. ALIGNMENT ACCURACY ±10 MS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG. A6-13-1977
AUSTIN, TEXAS 1-26-67 BROWN/SL

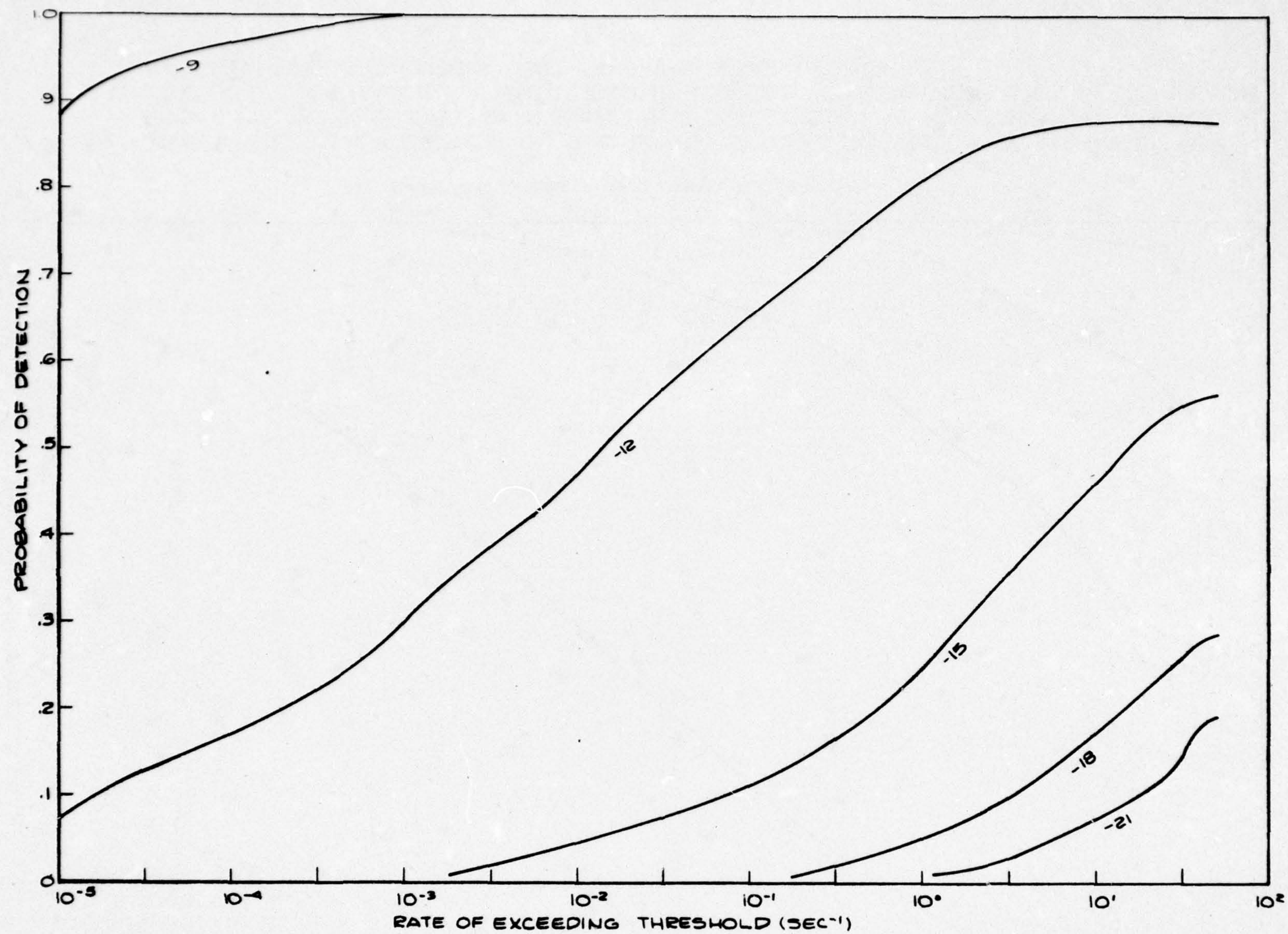

FIG. 23 - PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC DRTFM SIGNALS PROCESSED AS IN DIAGRAM FROM USN USL. ALIGNMENT ACCURACY ± 20 MS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG. A6-13-1978
AUSTIN, TEXAS 1-26-67 BROWN/SL

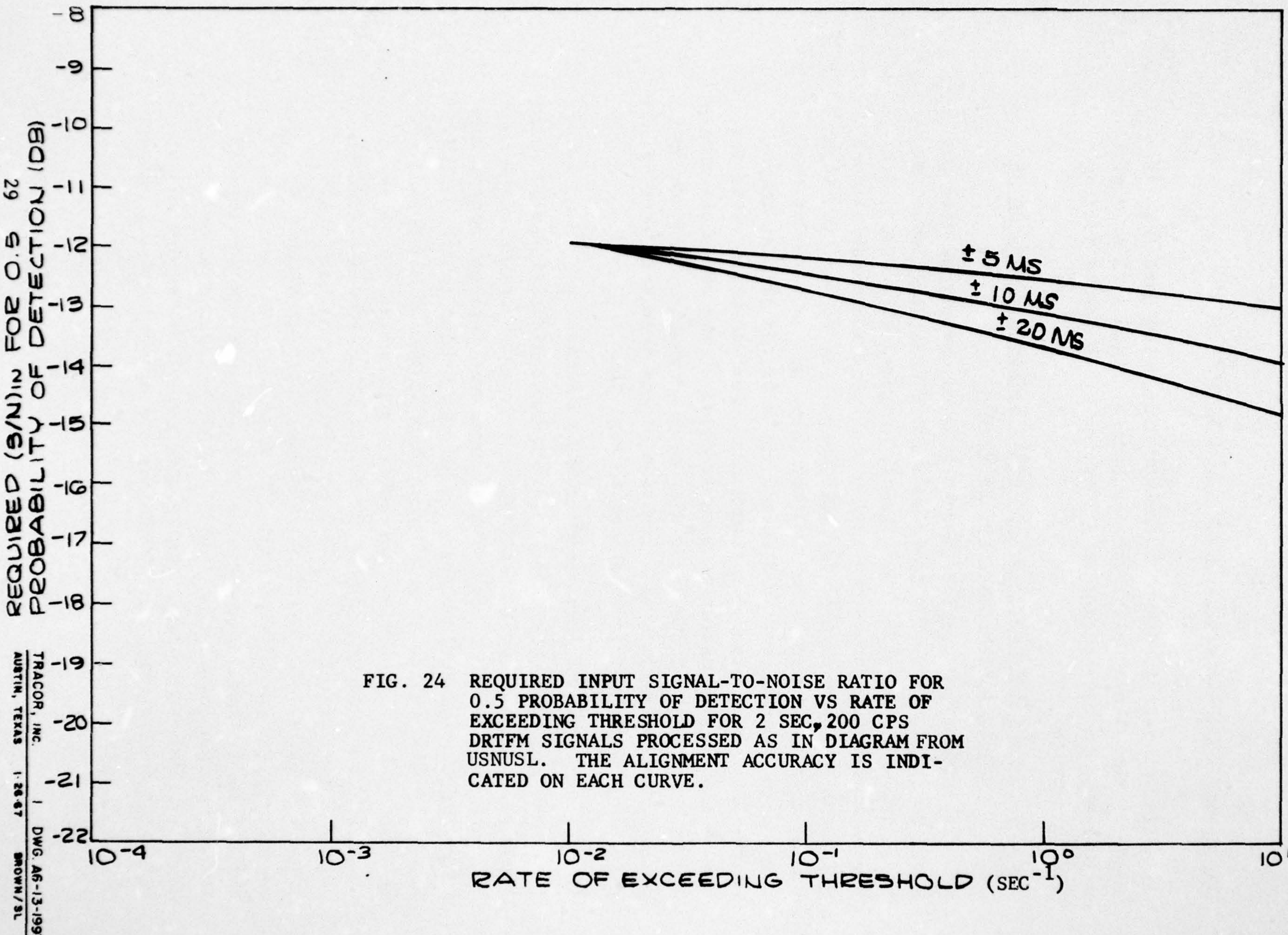

FIG. 24 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 2 SEC, 200 CPS DRTFM SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. THE ALIGNMENT ACCURACY IS INDICATED ON EACH CURVE.

of detection as a function of threshold crossing rate for all three of the allowed alignment accuracies. Figure 25 is a plot of threshold crossing rate as a function of threshold setting for this process.

1.8 Ideal 200 cps, 2 Second DRTFM Triplets Processed as in a Diagram Furnished by USNUSL

The DRTFM triplets were processed exactly as were the ideal DRTFM signals. The correlator references were identical to a single component of the signals. Figures 26, 27, and 28 give modified ROC curves for this process for the three allowed alignment accuracies as described above. As before, the input signal-to-noise ratios shown on each curve are in terms of the total signal power contained in all three of the triplet components. Figure 29 gives required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate for each of the three alignment accuracies. Figure 30 gives the crossing rate as a function of the threshold setting for this process and is identical to Fig. 25.

1.9 Summary of Ideal Signals and Triplets

Figure 31 gives the required input signal-to-noise ratio for a 0.5 probability of detection as a function of threshold crossing rate for the ideal signals processed through each of the four processors described above. The curve shown for the DRTFM signal is that for an alignment accuracy within ±5 milliseconds. Figure 32 gives the required input signal-to-noise ratio for a 0.5 probability of detection vs threshold crossing rate for each of the four processors operating on the ideal triplet signals. The DRTFM curve shown is for an alignment accuracy within ±5 milliseconds. As a general statement, the fully coherent correlation of the FM slides performed best, and the correlation by partial sums of FM slides performed nearly as well. The PRFM performance is considerably worse due to its much higher data rate. The DRTFM signals as shown here performed

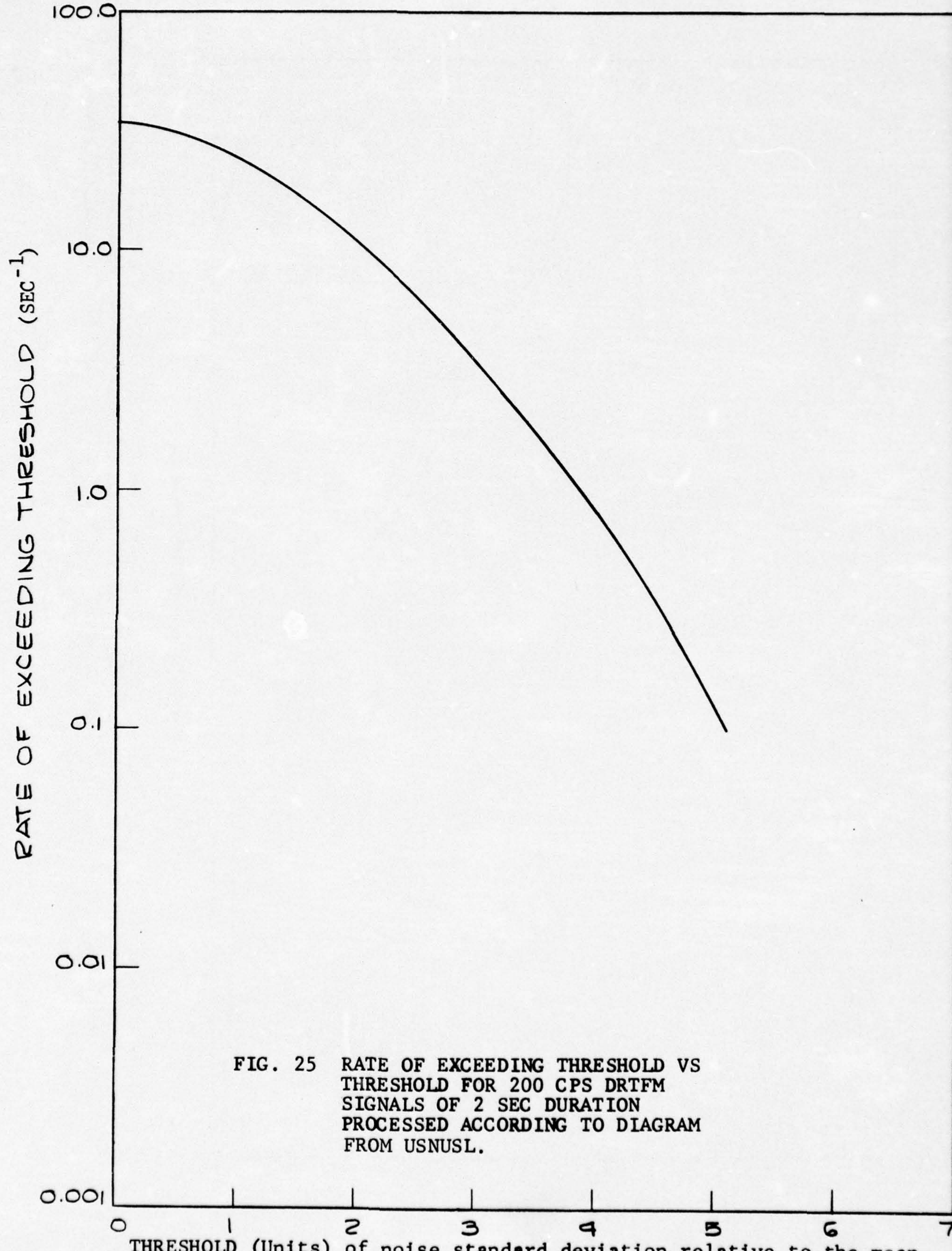

FIG. 25 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR 200 CPS DRTFM SIGNALS OF 2 SEC DURATION PROCESSED ACCORDING TO DIAGRAM FROM USNUSL.

TRACOR, INC. DWG. A6-13-1987
AUSTIN, TEXAS 1-26-67 BROWN/SL

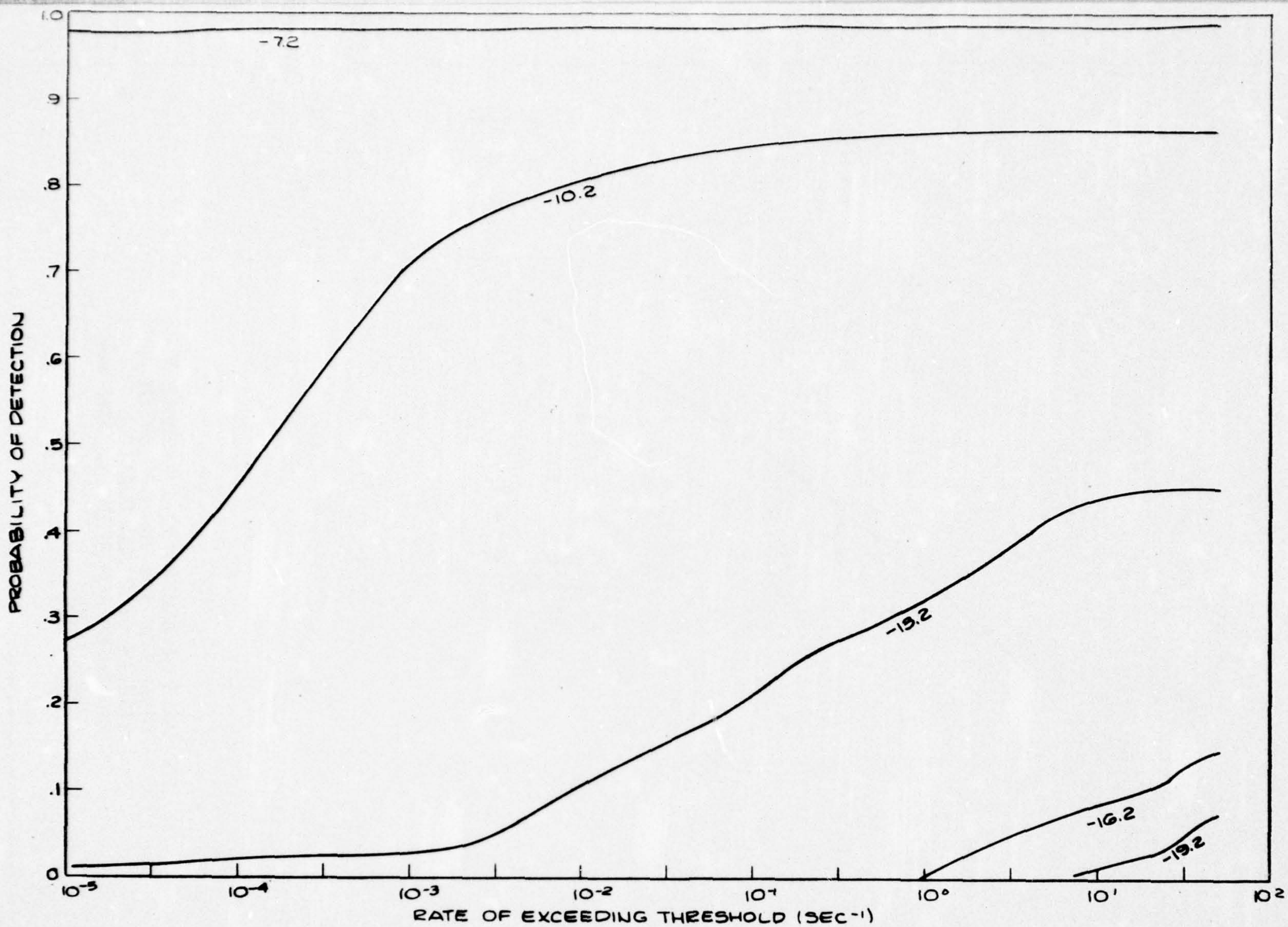

FIG. 26.—PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC. DRTFM TRIPLETS PROCESSED AS IN DIAGRAM FROM USN USL. ALIGNMENT ACCURACY ±5 MS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB

TRACOR, INC. DWG. A6-13-1981
AUSTIN, TEXAS 1-26-67 BROWN/SL

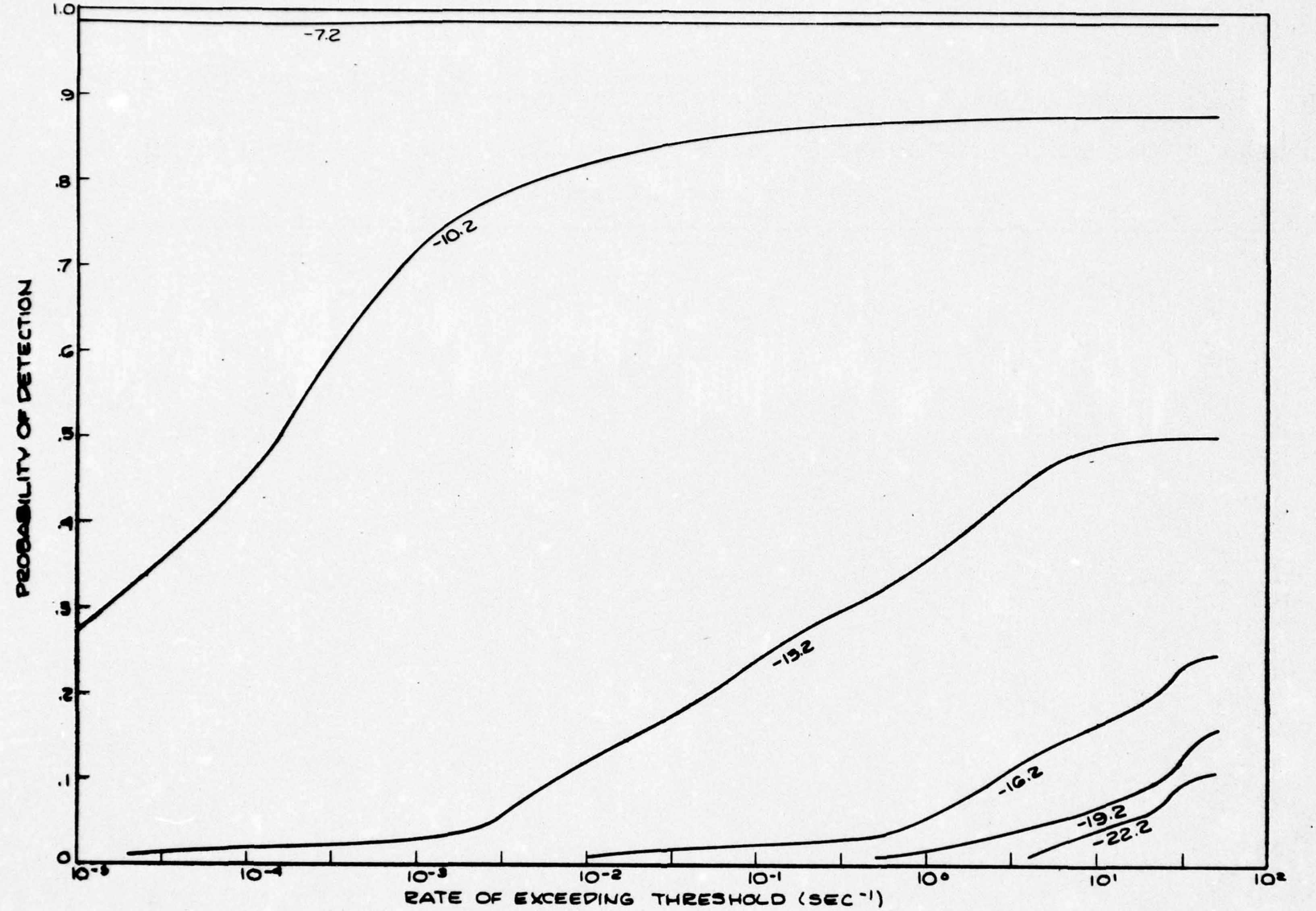

FIG. 27- PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC. DRTFM TRIPLETS PROCESSED AS IN DIAGRAM FROM USNUSL. ALIGNMENT ACCURACY ±10 MS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG. A6-13-1980
AUSTIN, TEXAS 1-26-67 BROWN/SL

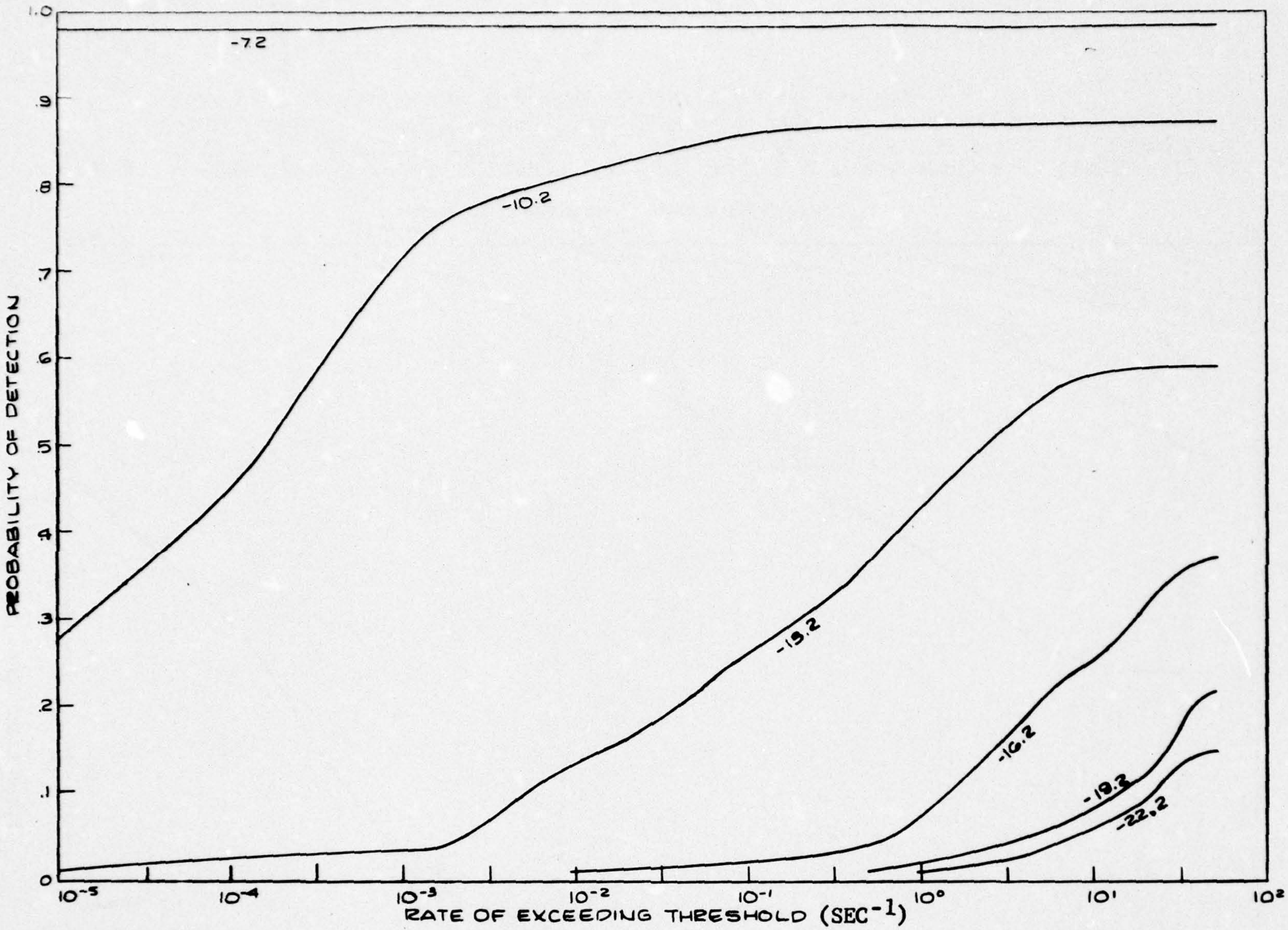

FIG. 28- PROBABILITY OF DETECTION VS. RATE OF EXCEEDING THRESHOLD FOR 200 CPS 2 SEC. DRTFM TRIPLETS PROCESSED AS IN DIAGRAM FROM USN USL. ALIGNMENT ACCURACY ± 20 MS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN DB.

TRACOR, INC. DWG A6-13-1970
AUSTIN, TEXAS 1-26-67 BROWN/SL

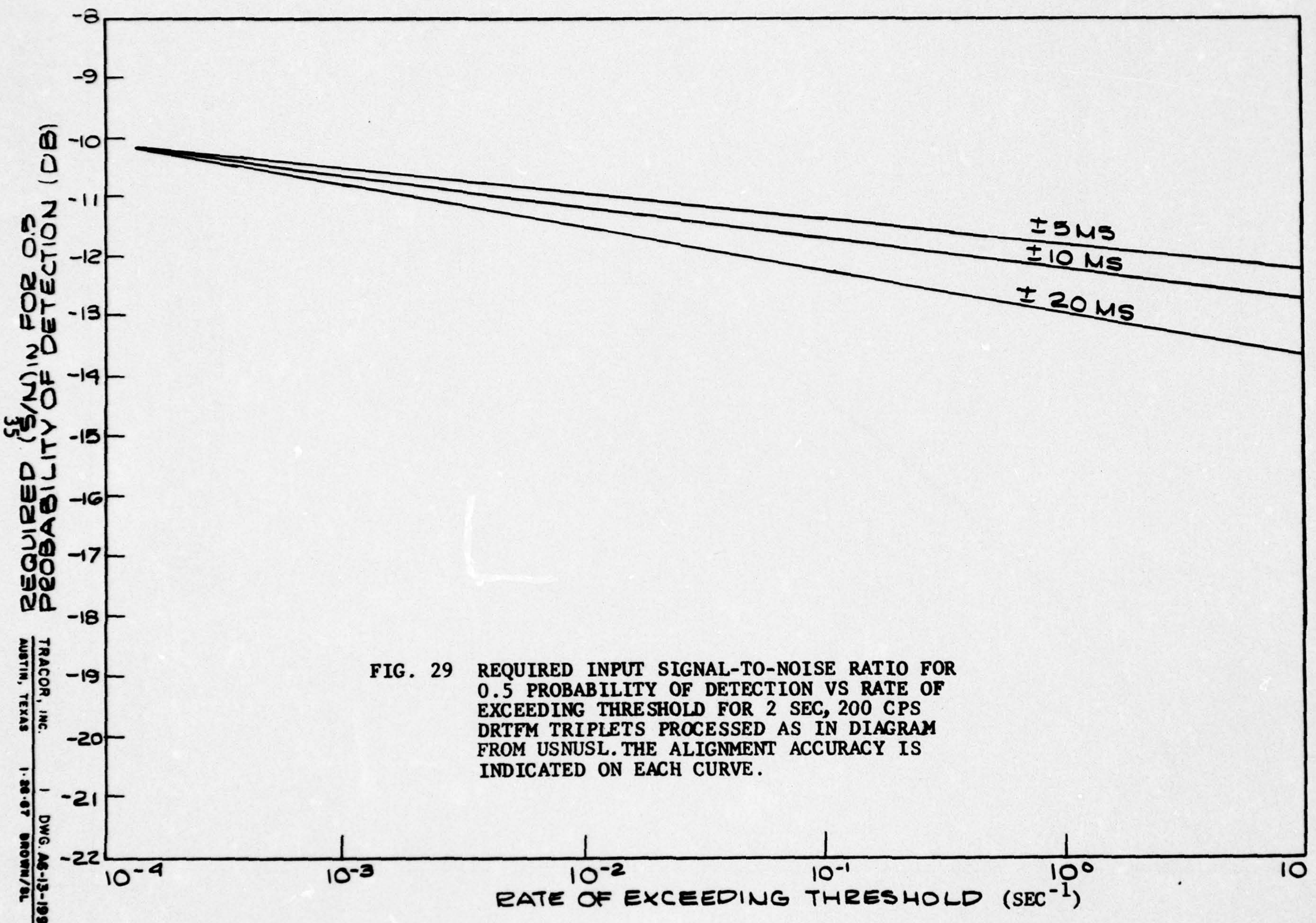

FIG. 29 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 2 SEC, 200 CPS DRTFM TRIPLETS PROCESSED AS IN DIAGRAM FROM USNUSL. THE ALIGNMENT ACCURACY IS INDICATED ON EACH CURVE.

TRACOR, INC. AUSTIN, TEXAS | DWG. A6-13-1990 BROWN/BL

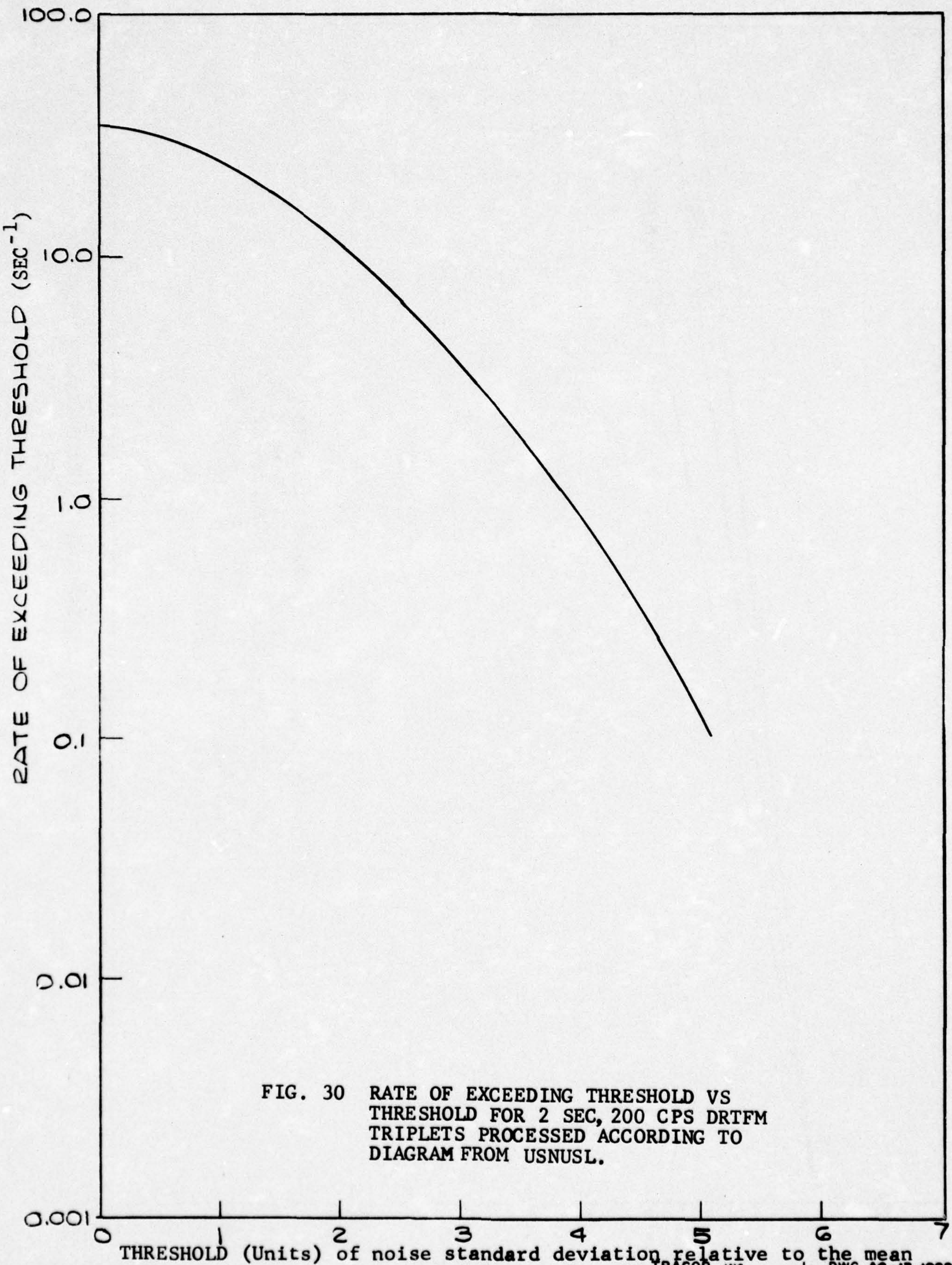

FIG. 30 RATE OF EXCEEDING THRESHOLD VS THRESHOLD FOR 2 SEC, 200 CPS DRTFM TRIPLETS PROCESSED ACCORDING TO DIAGRAM FROM USNUSL.

TRACOR, INC. | DWG. A6-13-1982
AUSTIN, TEXAS 1-26-67 BROWN/SL

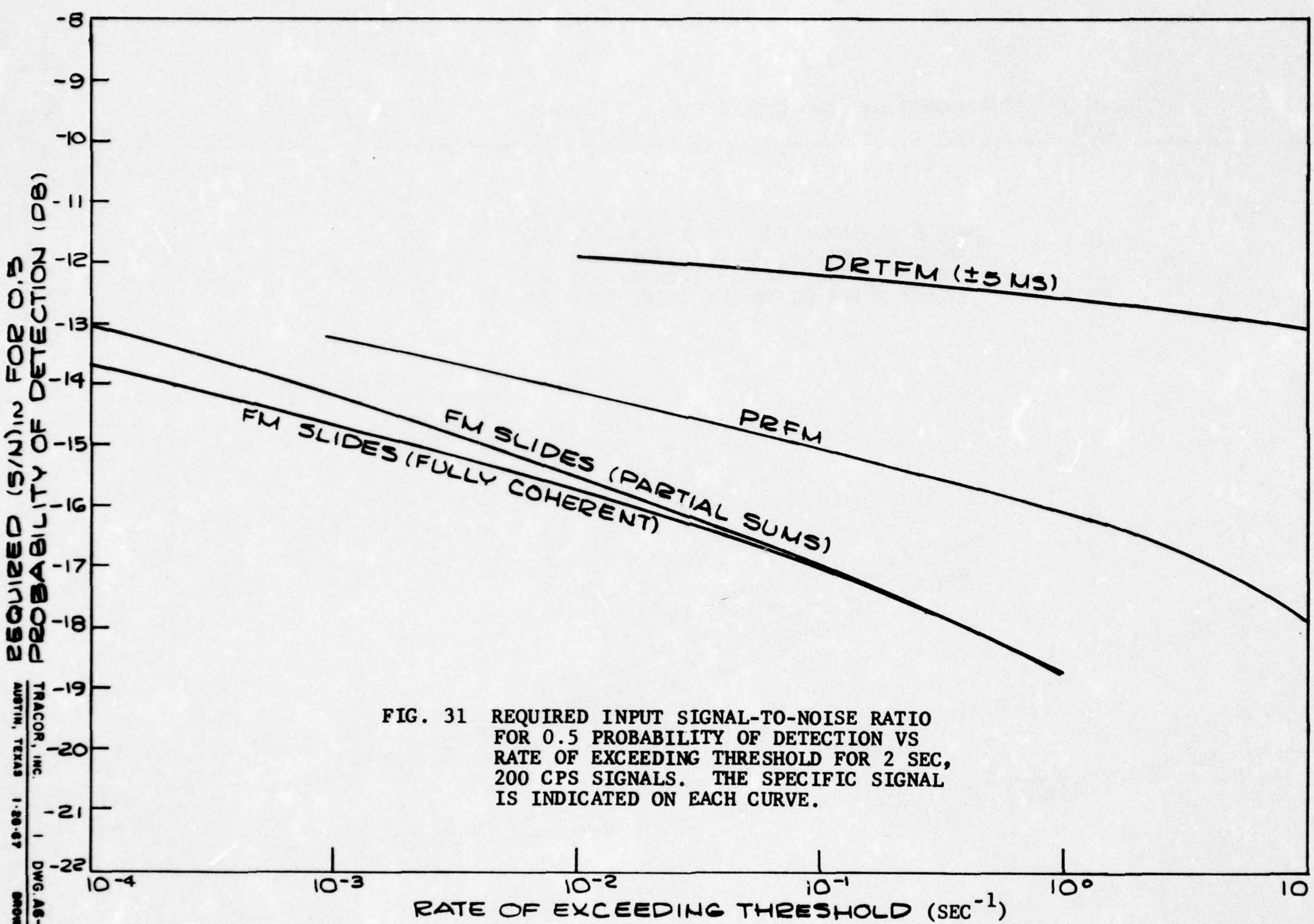

FIG. 31 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 2 SEC, 200 CPS SIGNALS. THE SPECIFIC SIGNAL IS INDICATED ON EACH CURVE.

TRACOR, INC. | DWG. A6-13-1991
AUSTIN, TEXAS 1-20-67 BROWN/SL

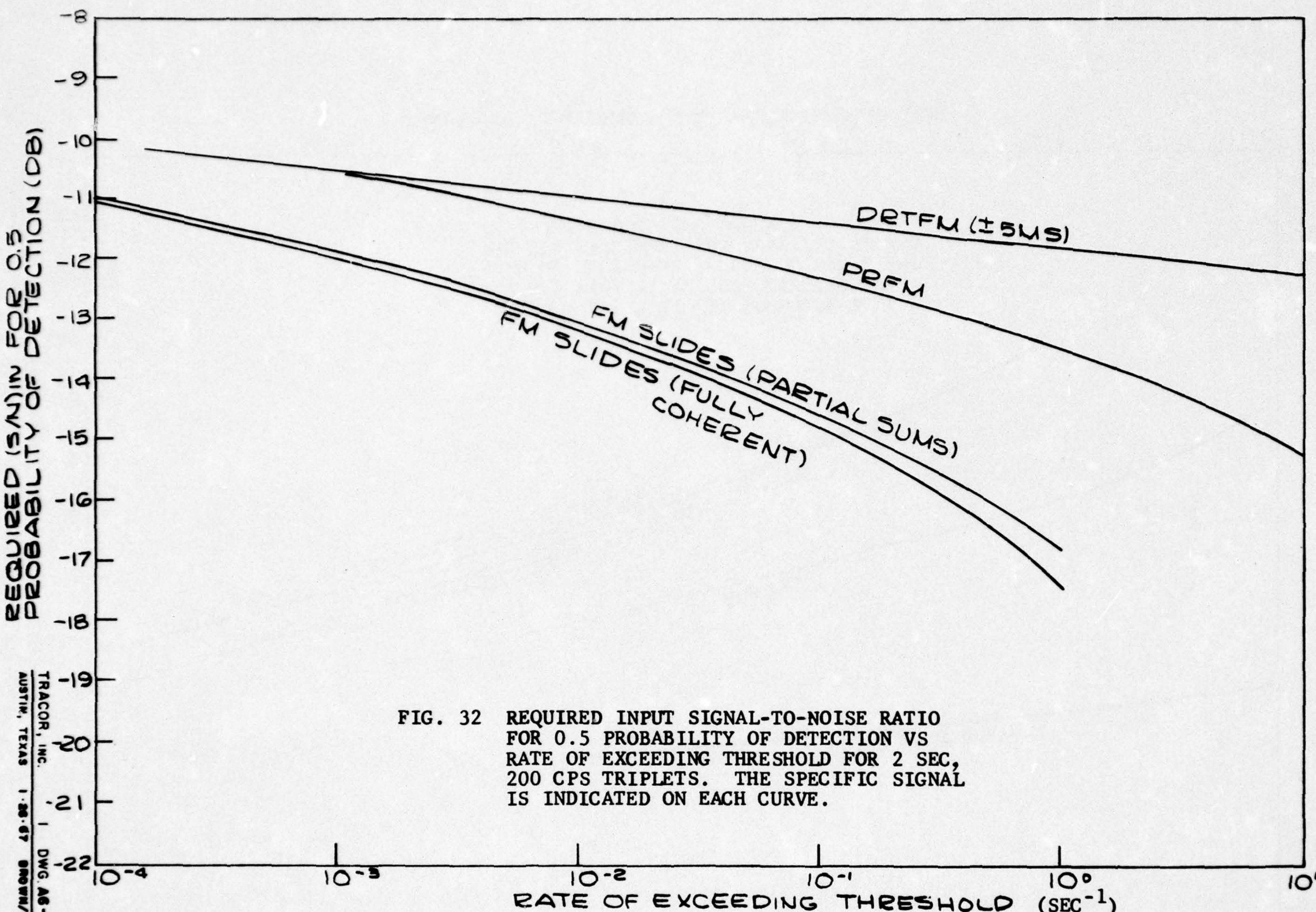

FIG. 32 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 2 SEC, 200 CPS TRIPLETS. THE SPECIFIC SIGNAL IS INDICATED ON EACH CURVE.

TRACOR, INC. AUSTIN, TEXAS 1·26·67 DWG. A6-13-1992 BROWN/SL

worst, but it is noteworthy that they performed much better on the ideal triplets relative to the other processors. This at least encourages one to investigate the relative performance of the various processors when used on other types of structured signals.

2. OTHER STRUCTURED SIGNALS

In order to study the performance degradations caused by other types of structured signals, a statistical model was designed to describe the signals. The model assumes that a structured echo consists of the summation of several ideal signals which have been shifted in Doppler and time and scaled in amplitude. The amplitude of each component is also allowed to vary. In this model the Doppler, the time delay, and the intensity given in dB are all assumed to obey Gaussian distributions which are truncated at $\pm 3\sigma$. Any number of components may be used in the signals, and the resulting composite signals are normalized to have the same total power. For the present study, signals were generated having 6 components. The standard deviation of the Doppler shifts was 3 cycles per second, the standard deviation of the time shifts was 20 milliseconds, and the standard deviation of the amplitude distribution was 3 dB. Four typical examples of 2 sec, 200 cps FM slide signals generated in this way are shown in Fig. 33. Below each signal is a correlogram of the signal which resulted by linearly correlating the generated signal with an ideal FM slide. Table I shows the actual values of time and Doppler shift for each component of these four signals as well as the fraction of the signal power contained in that component and the expected peak shift after the signal is correlated. At the present, only FM slide type signals have been generated. This is sufficient to investigate both the FM slide and the DRTFM signals. One hundred signals of both types have been generated. These signals were added to noise at various signal-to-noise ratios and passed through several of the above described processors. The results are described below. The signals generated as described above will be referred to as "jittered signals."

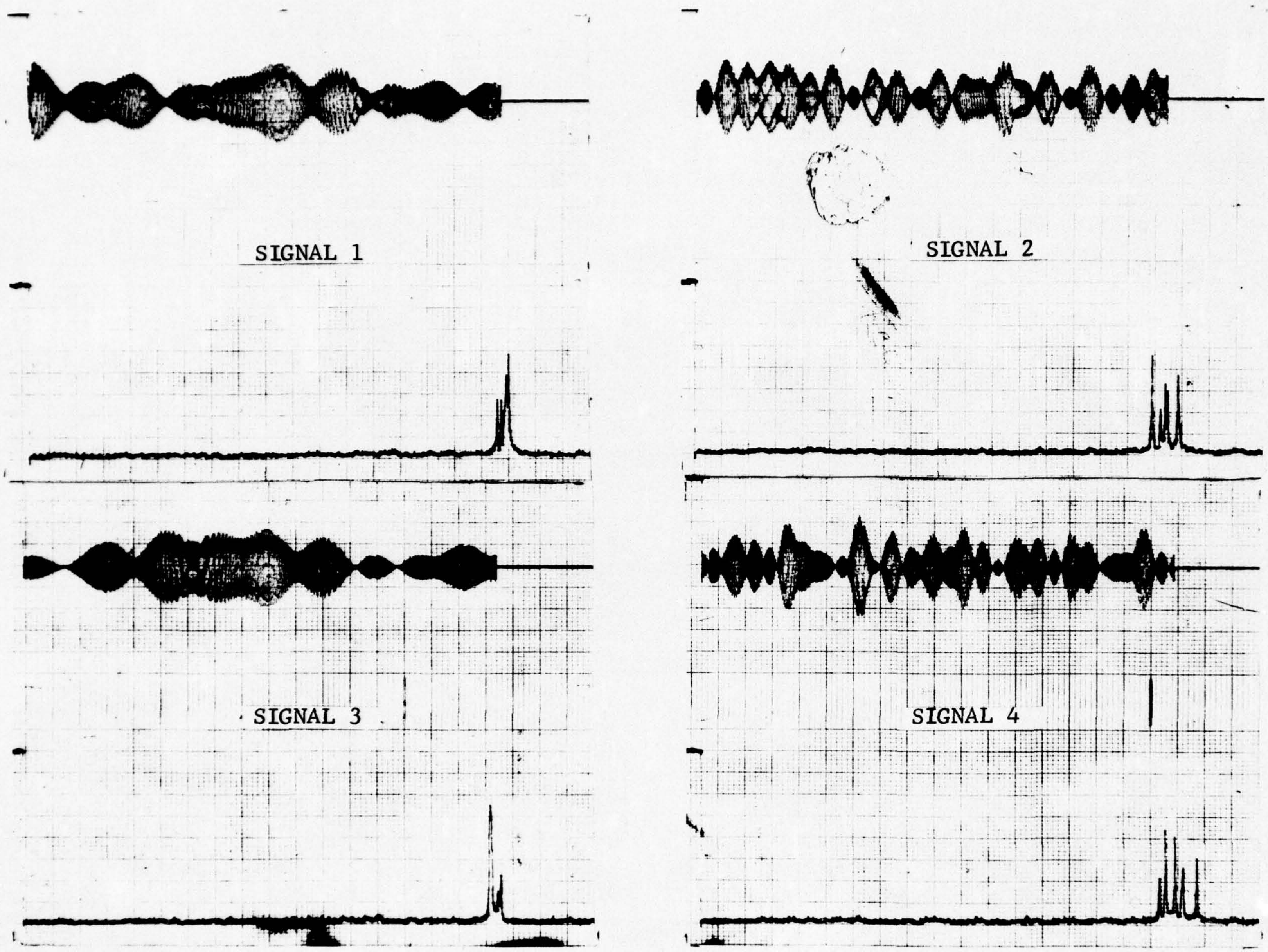

FIG. 33 SOME TYPICAL "JITTERED" 200 CPS FM SLIDE SIGNALS OF 2 SEC DURATION AND THEIR CORRELOGRAMS

TRACOR, INC. DWG. A6-13-2000
AUSTIN, TEXAS 1-26-67 BROWN/SL

TABLE I

Characteristics of Jittered Signals

COMPONENT	DOPPLER SHIFT (cps)	TIME SHIFT (sec)	FRACTION OF POWER IN COMPONENT	PEAK SHIFT AT CORRELATOR OUTPUT
SIGNAL 1				
1	0.0561832	0.0193864	0.0967401	0.0199482
2	-0.7257411	-0.0111936	0.2497188	-0.0184510
3	2.2877507	-0.0191208	0.0999354	0.0037567
4	0.0936560	-0.0073755	0.0392629	-0.0064389
5	-2.3553818	0.0115866	0.1214475	-0.0119673
6	-2.6389537	-0.0002913	0.3928952	-0.0266808
SIGNAL 2				
1	-5.5865114	0.0057891	0.1000302	-0.0500760
2	2.9892023	0.0333049	0.2327274	0.0631969
3	1.0528831	-0.0035592	0.1411158	0.0069697
4	0.5847853	0.0221042	0.0482932	0.0279521
5	-0.8945057	-0.0062256	0.1026044	-0.0027194
6	-3.0939513	-0.0171062	0.3752290	-0.0480457
SIGNAL 3				
1	0.0062413	-0.0185995	0.1073864	-0.0185371
2	0.5338761	0.0212036	0.2694975	0.0265424
3	2.3724769	-0.0036439	0.3302984	0.0200809
4	-0.0436958	0.0230520	0.0677257	0.0226150
5	5.4506465	-0.0247578	0.1684017	0.0297487
6	-0.3442747	-0.0037287	0.0566904	-0.0071715
SIGNAL 4				
1	-0.0062413	-0.0323425	0.0628026	-0.0324049
2	-0.4578087	0.0000416	0.2688863	-0.0045365
3	-4.3277443	0.0045810	0.1050963	-0.0386965
4	2.7325012	0.0339920	0.0807773	0.0613170
5	2.6574563	0.0101343	0.3168894	0.0367089
6	-8.2396178	-0.0140497	0.1655481	-0.0964459

2.1 <u>Full Correlation of Jittered FM Slide Signals Using an Ideal FM Slide Signal as a Reference</u>

The processor used here is the same as that described before for use on ideal signals and ideal triplets. It consists of a linear replica correlator followed by a linear rectifier and a perfect averager. Two sets of modified ROC curves were obtained for this process. The first set, shown in Fig. 34, describes the process when a five millisecond averaging time is used. The second set of modified ROC curves, shown in Fig. 35, describes the process for a 50 millisecond averaging time. There is very little apparent difference in the two sets of curves although the overaveraging seems to give a very slight advantage at the small signal-to-noise ratios. Figure 36 was obtained from Figs. 34 and 35. This figure is the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate for the two processes described in Figs. 34 and 35.

2.2 <u>Correlation by Partial Sums of the Jittered FM Slide Signals</u>

Partial sums correlation was performed for the jittered FM slide signals by both two-piece and eight-piece partial sums correlators.

Two sets of modified ROC curves were obtained using two-piece partial sums correlation. The set shown in Fig. 37 is the result of using the ideal 10 ms averaging time on each channel, and the set shown in Fig. 38 was obtained by using a 50 ms time constant on each channel. The set of modified ROC curves shown in Fig. 39 represents the results of partial sums correlation with eight references of 25 cps bandwidth and 250 ms duration.

Figure 40 was obtained from Figs. 37, 38 and 39. This figure gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate for the three partial sums processors described.

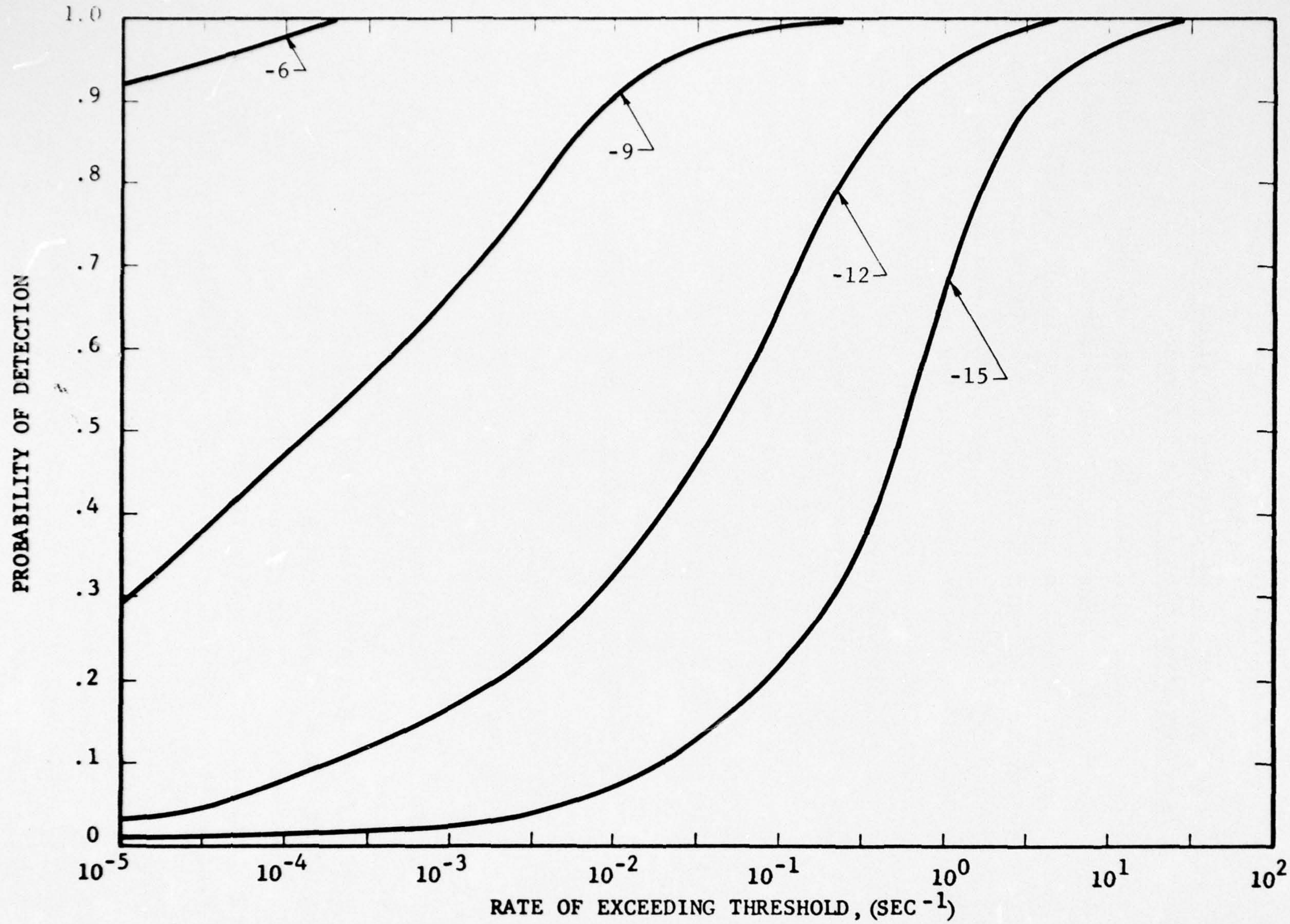

FIG. 34 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULL CORRELATION OF JITTERED FM SLIDE SIGNALS WITH 200 CPS BANDWIDTH AND 2 SECOND DURATION. THE AVERAGING TIME USED IS 5 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

TRACOR, INC. | DWG. 6-13-302
AUSTIN, TEXAS 3-16-66 BROWN/SL

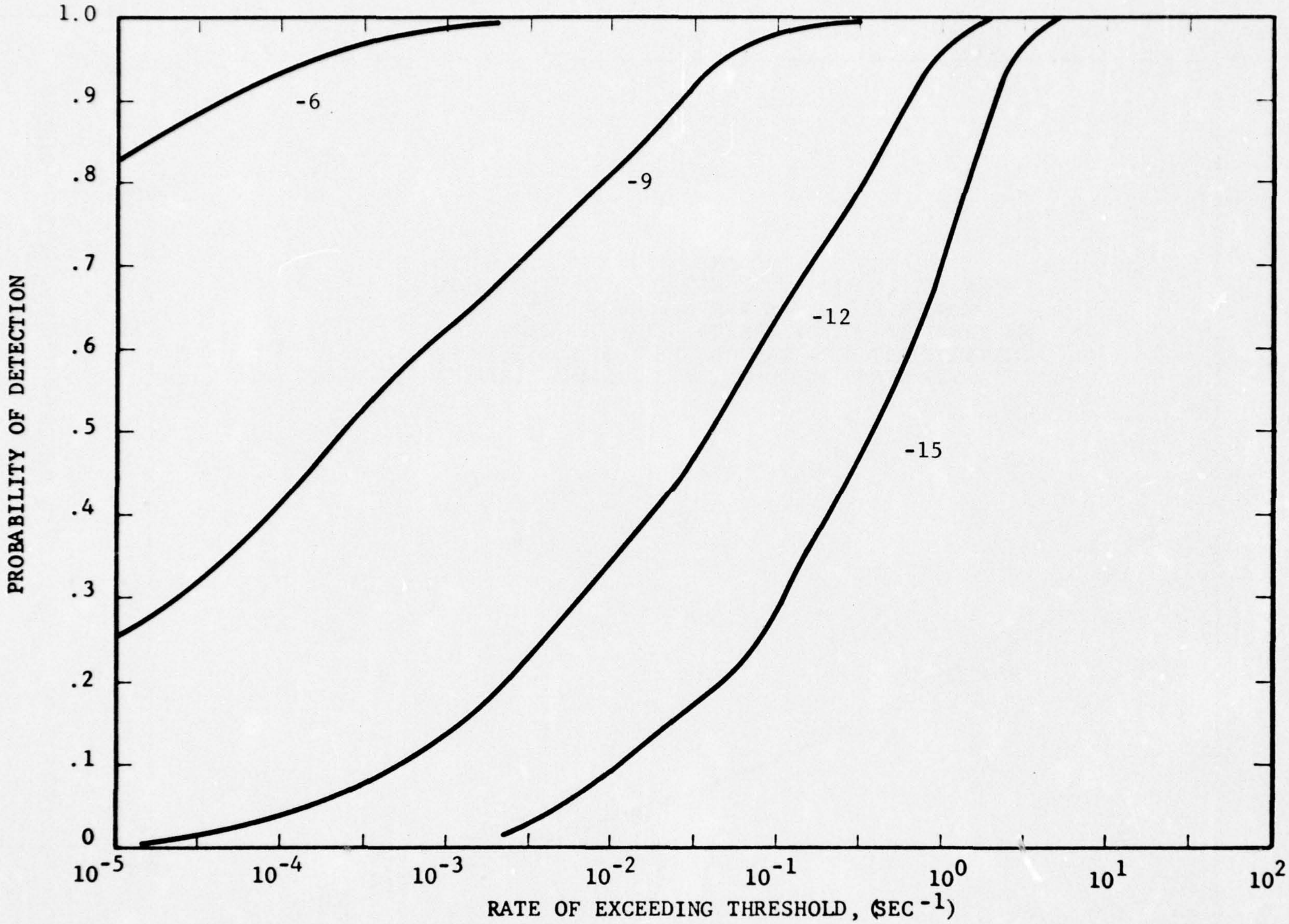

FIG. 35 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULL CORRELATION OF JITTERED FM SLIDE SIGNALS WITH 200 CPS BANDWIDTH AND 2 SECOND DURATION. THE AVERAGING TIME USED WAS 50 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

TRACOR, INC. | DWG. 6-13-317
AUSTIN, TEXAS 3-16-66 BROWN/SL

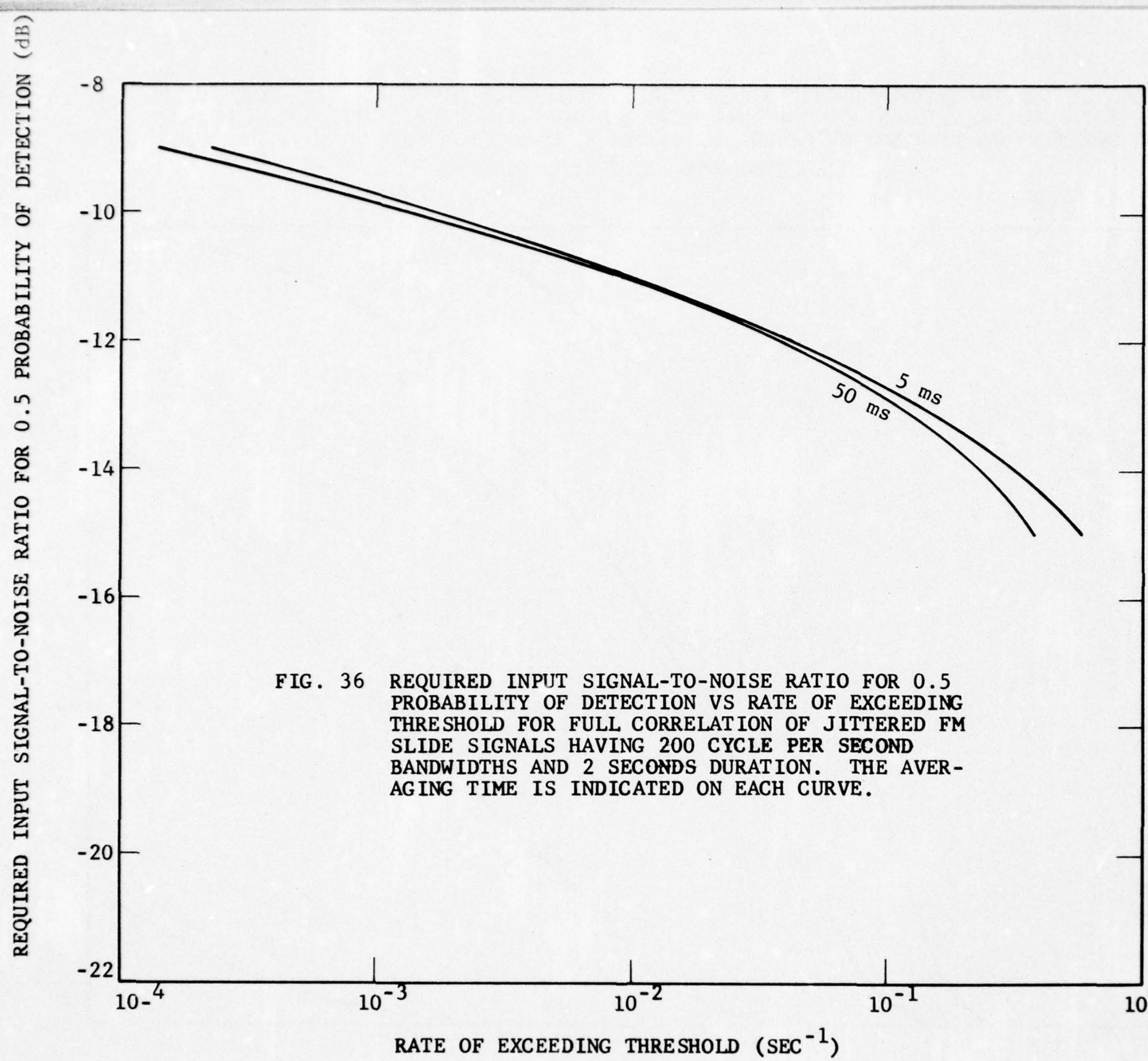

FIG. 36 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR FULL CORRELATION OF JITTERED FM SLIDE SIGNALS HAVING 200 CYCLE PER SECOND BANDWIDTHS AND 2 SECONDS DURATION. THE AVERAGING TIME IS INDICATED ON EACH CURVE.

TRACOR, INC. | DWG. 6-13-294
AUSTIN, TEXAS 3-15-66 BROWN/SL

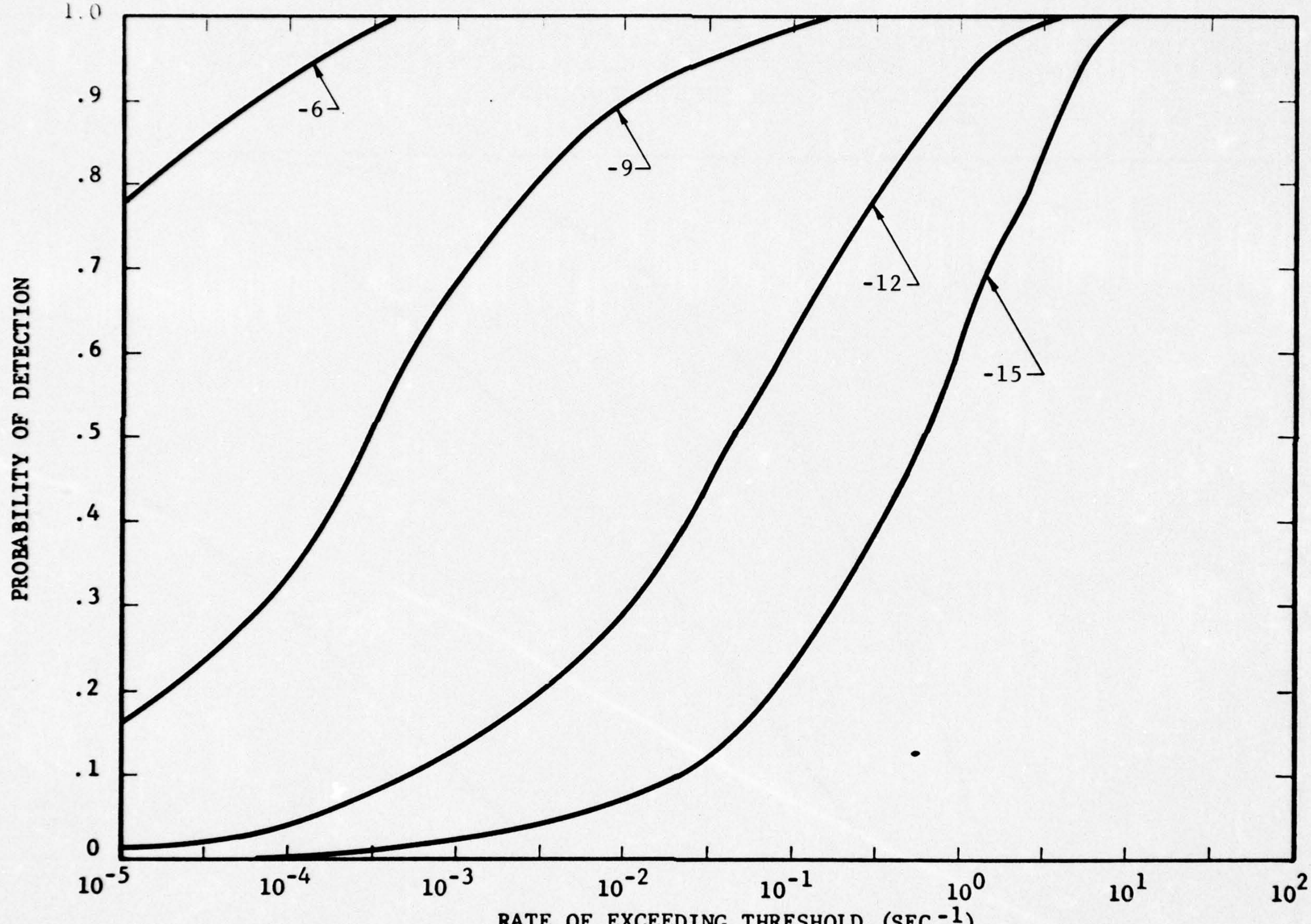

FIG. 37 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 200 CPS JITTERED FM SLIDES OF 2 SECOND DURATION. 10 MILLISECONDS AVERAGING WAS USED ON EACH CHANNEL. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

TRACOR, INC. | DWG. 6-13-304
AUSTIN, TEXAS | 3-16-66 BROWN/SL

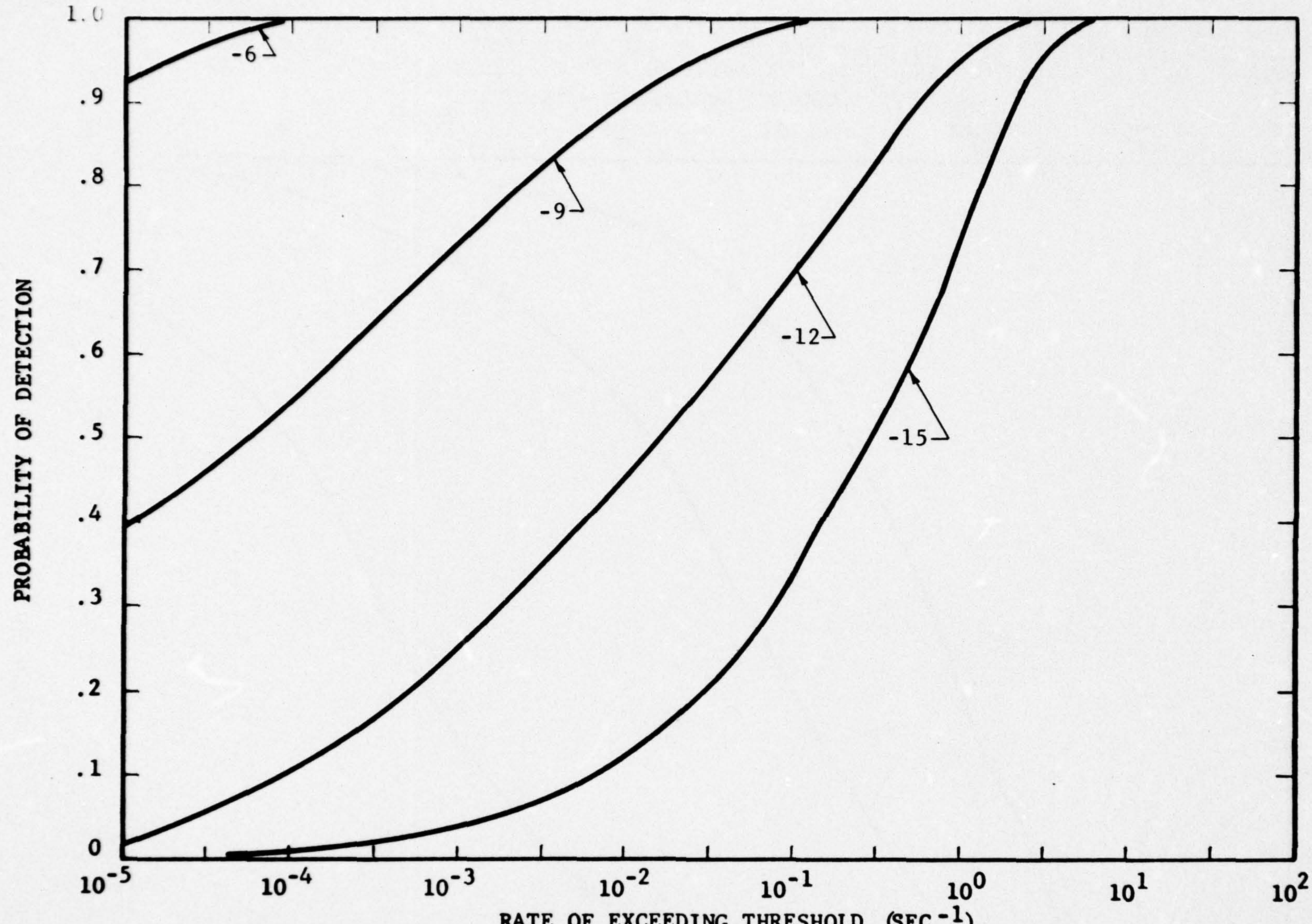

FIG. 38 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 200 CPS JITTERED FM SLIDES OF 2 SECOND DURATION. 50 MILLISECONDS AVERAGING WAS USED ON EACH CHANNEL. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

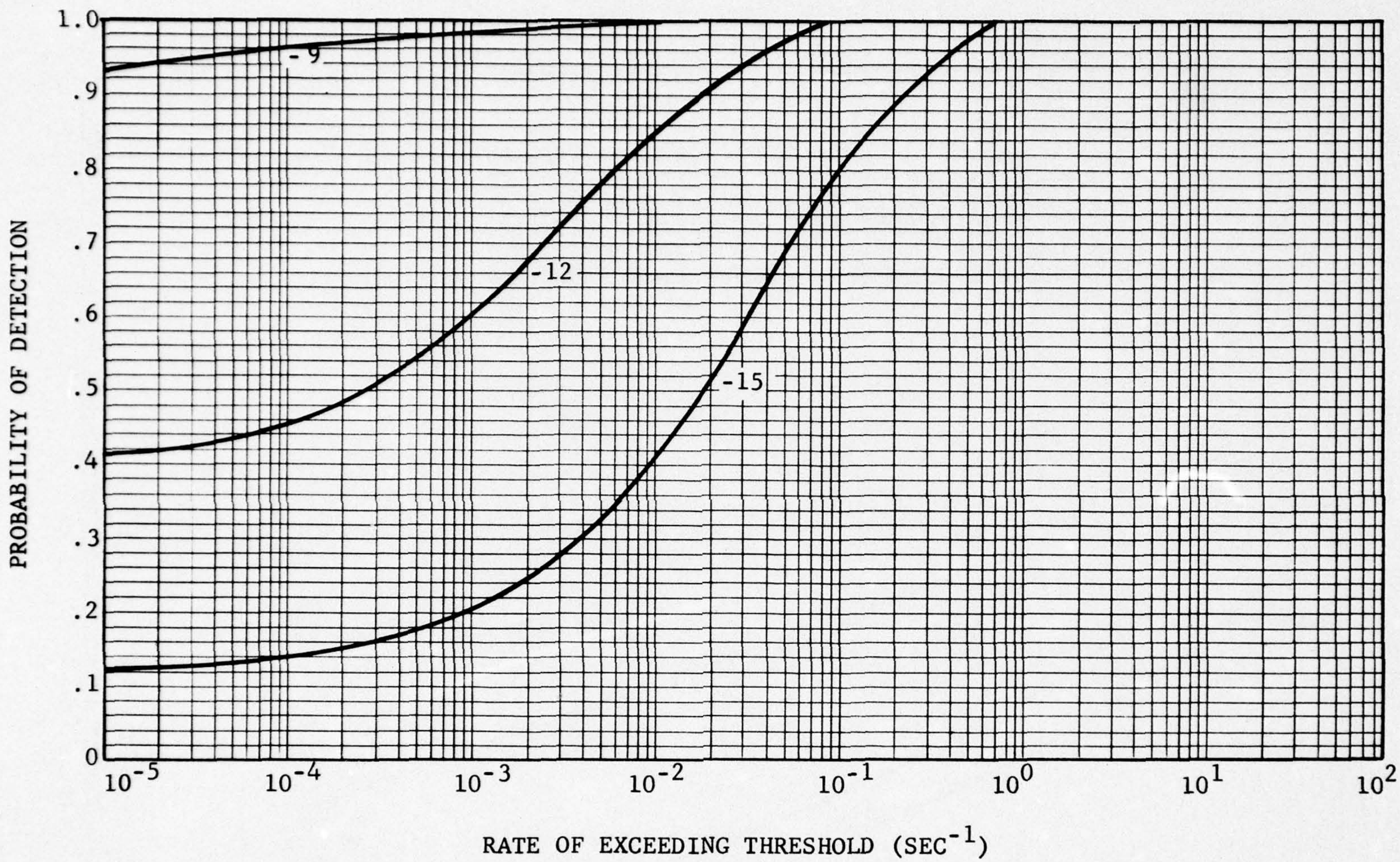

FIG. 39 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC JITTERED FM SLIDE SIGNALS CORRELATED BY PARTIAL SUMS IN EIGHT SECTIONS. EACH CHANNEL WAS RECTIFIED AND AVERAGED FOR 40 MSEC BEFORE SUMMING. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

TRACOR, INC. DWG. A6-13-2005
AUSTIN, TEXAS 1-26-67 BROWN/SL

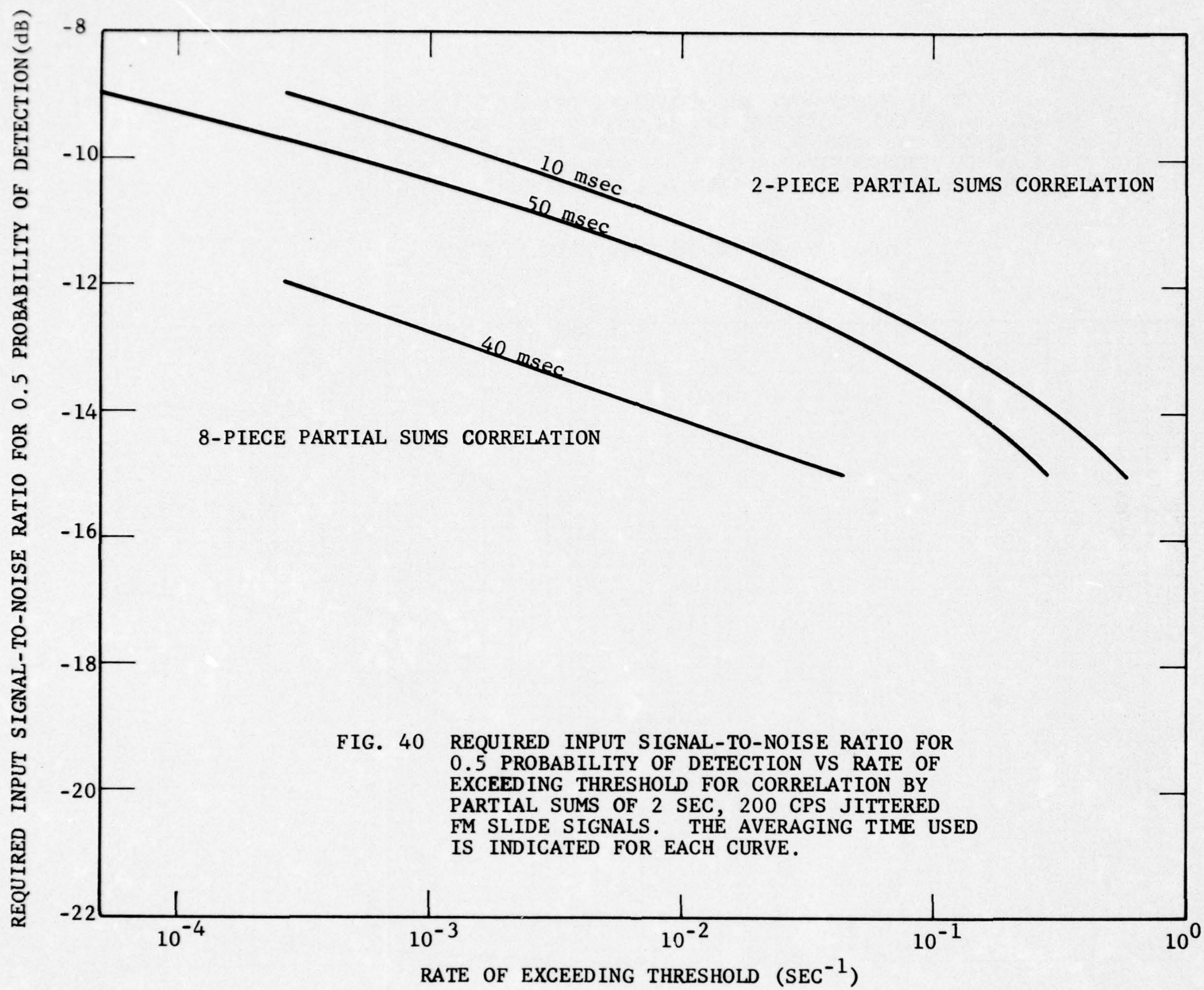

FIG. 40 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR CORRELATION BY PARTIAL SUMS OF 2 SEC, 200 CPS JITTERED FM SLIDE SIGNALS. THE AVERAGING TIME USED IS INDICATED FOR EACH CURVE.

TRACOR, INC. DWG. A6-13-2010
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2.3 Jittered DRTFM Signals Processed as in Diagram Furnished by USNUSL

As noted before, this processor improved in performance relative to the other processors when the ideal triplet signals were used rather than the ideal signals. These ideal triplets were made up of three overlapped ideal signals. The signals were delayed in time only and summed up. For this type of "time delay only" situation the structure at the outputs of the correlators in each of the two channels will appear quite similar. Thus when these two structures are correlated against each other a peak will occur at a predictable point. The point at which this peak occurs is required in order to realign the two channels for summing. Thus for "time delay only" structuring, the processor performs relatively well. On the other hand, if one were to consider structuring which consisted of summing up component signals which had been shifted in Doppler only, the structures in the two channels would be mirror images. Thus some sort of inversion process might be carried out on one of the channels, in which case the processor would perform very much as it does with time only structuring. A difficulty arises, however, when a combination of time delay and Doppler shift structuring is allowed. This type of signal causes the structure in one channel to differ in form from that in the other channel. Furthermore, these differences vary in an unpredictable manner from signal to signal. When these mismatched structures are correlated against each other a correlation peak varies in position from signal to signal. Thus proper alignment of the two channels for recombination is less predictable. As before, three sets of modified ROC curves were obtained on this processor. These correspond to alignment accuracies within ±5 milliseconds, ±10 milliseconds, and ±20 milliseconds respectively. The three sets of curves are shown in Figs. 41, 42, and 43. The largest input signal-to-noise ratio used was 0 dB, related, of course, to the total energy in the structured signal. It is noted that even in Fig. 43, where accuracies were within ±20 milliseconds

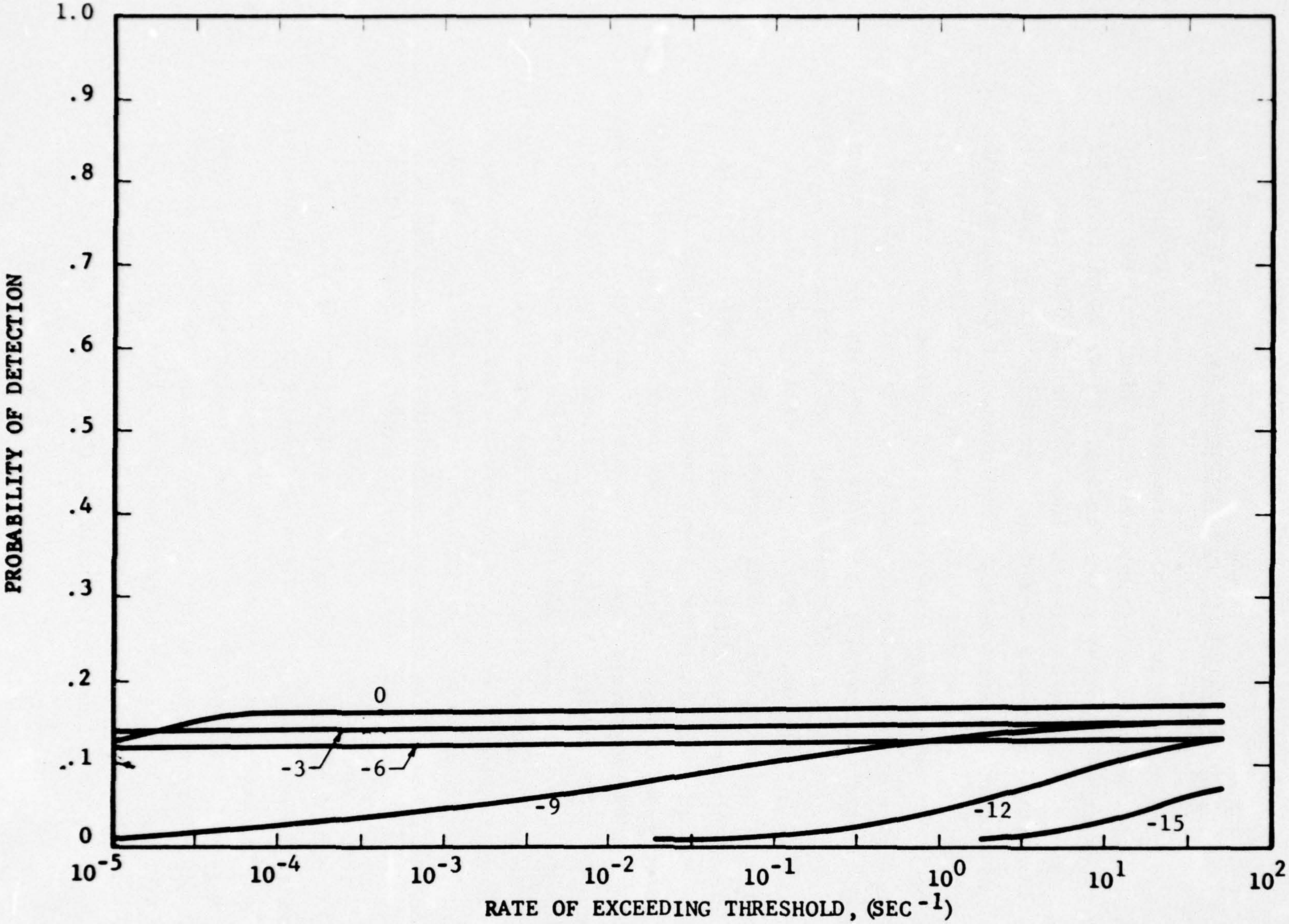

FIG. 41 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND JITTERED DRTFM SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. ALIGNMENT ACCURACY ±5 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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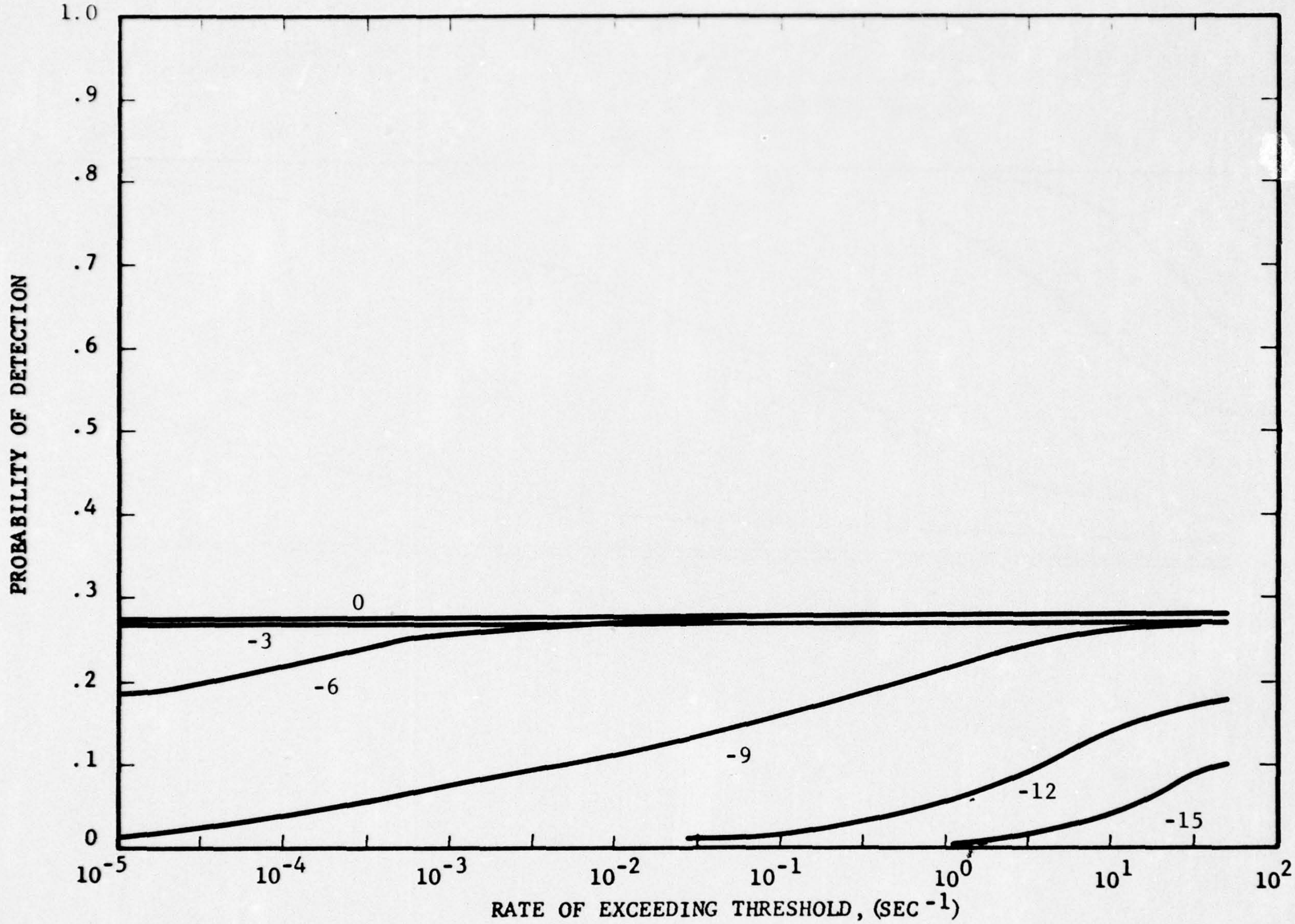

FIG. 42 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND JITTERED DRTFM SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. ALIGNMENT ACCURACY ±10 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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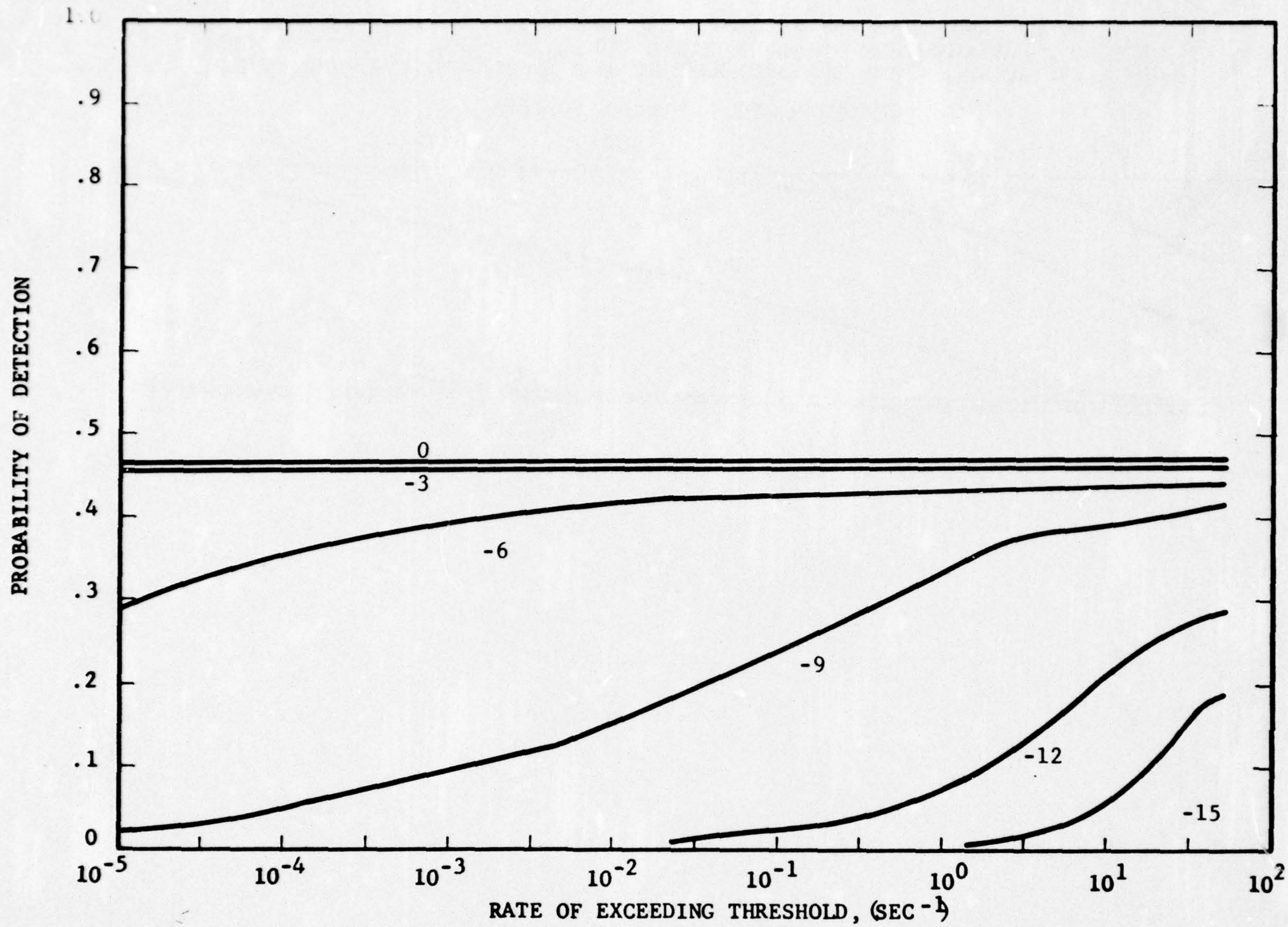

FIG. 43 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND JITTERED DRTFM SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. ALIGNMENT ACCURACY ±20 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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no more than about 0.47 of the signals were detected. In order to demonstrate the effect which the combination of Doppler and time shifts has on the DRTFM signals, some Sanborn recordings were made. Figure 44 shows some of the typical signals that were actually used in the simulation. The top channel shows the raw FM slide signals running from 200 to 300 cycles while the second channel shows the raw signals running from 400 to 300 cycles per second. To reiterate, each of these signals consists of a sum of 6 individual component signals each of which has had an appropriate time delay and Doppler shift applied to it. Channels 3 and 4 show correlograms for channels 1 and 2 respectively. These were obtained by correlating the signals on channels 1 and 2 with the appropriate ideal FM slide. It is noted that the structures appearing in channels 3 and 4 differ from each other considerably. For comparison purposes, upsliding FM signals were generated in each of the two bands. These are shown in Fig. 45. Channel 1 shows the raw jittered signals running from 200 to 300 cycles and channel 2 shows the raw signals running from 300 to 400 cycles. Channels 3 and 4 are again correlograms of channels 1 and 2 respectively. Since the signals are in two different frequency bands, the phase differences caused by time delays and Doppler shifts will vary from one band to the other. This prevents the signals from looking identical in structure. However, if one examines channels 3 and 4 he will find that although the amplitudes of the correlation peaks vary, the positions at which they occur correspond quite closely. Thus if channels 3 and 4 were correlated against each other a peak would occur in a much more predictable location from signal to signal than those for the DRTFM signals. To verify this, these signals were passed through the same processor used on the DRTFM signals with both of the correlator references being upslides in this case. Three sets of modified ROC curves were obtained, corresponding to alignment accuracies within ±5, ±10 milliseconds and ±20 milliseconds. These curves are shown in Figs. 46, 47, and 48 respectively. The

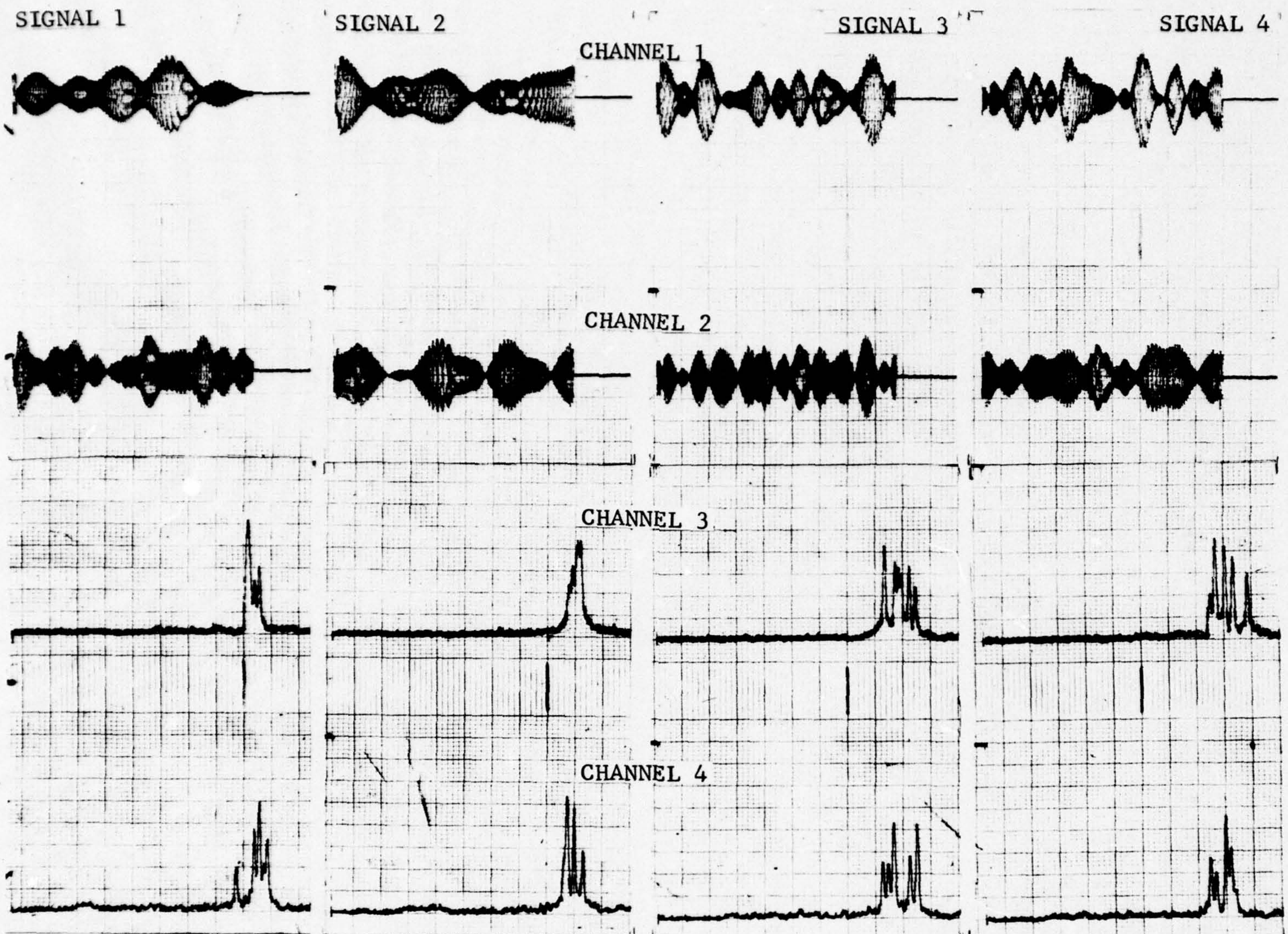

FIG. 44 FOUR TYPICAL PAIRS OF JITTERED FM SLIDE SIGNALS AND THEIR CORRELOGRAMS. CHANNEL 1 SHOWS SIGNALS RUNNING FROM 200 CPS TO 300 CPS, AND CHANNEL 2 SHOWS SIGNALS RUNNING FROM 400 CPS TO 300 CPS. THE VALUES OF TIME SHIFT, DOPPLER SHIFT, AND INTENSITY APPLIED TO EACH COMPONENT ARE IDENTICAL FOR BOTH THE UP SLIDES AND THE DOWN SLIDES. CHANNELS 3 AND 4 SHOW CORRELOGRAMS OF CHANNELS 1 AND 2 RESPECTIVELY.

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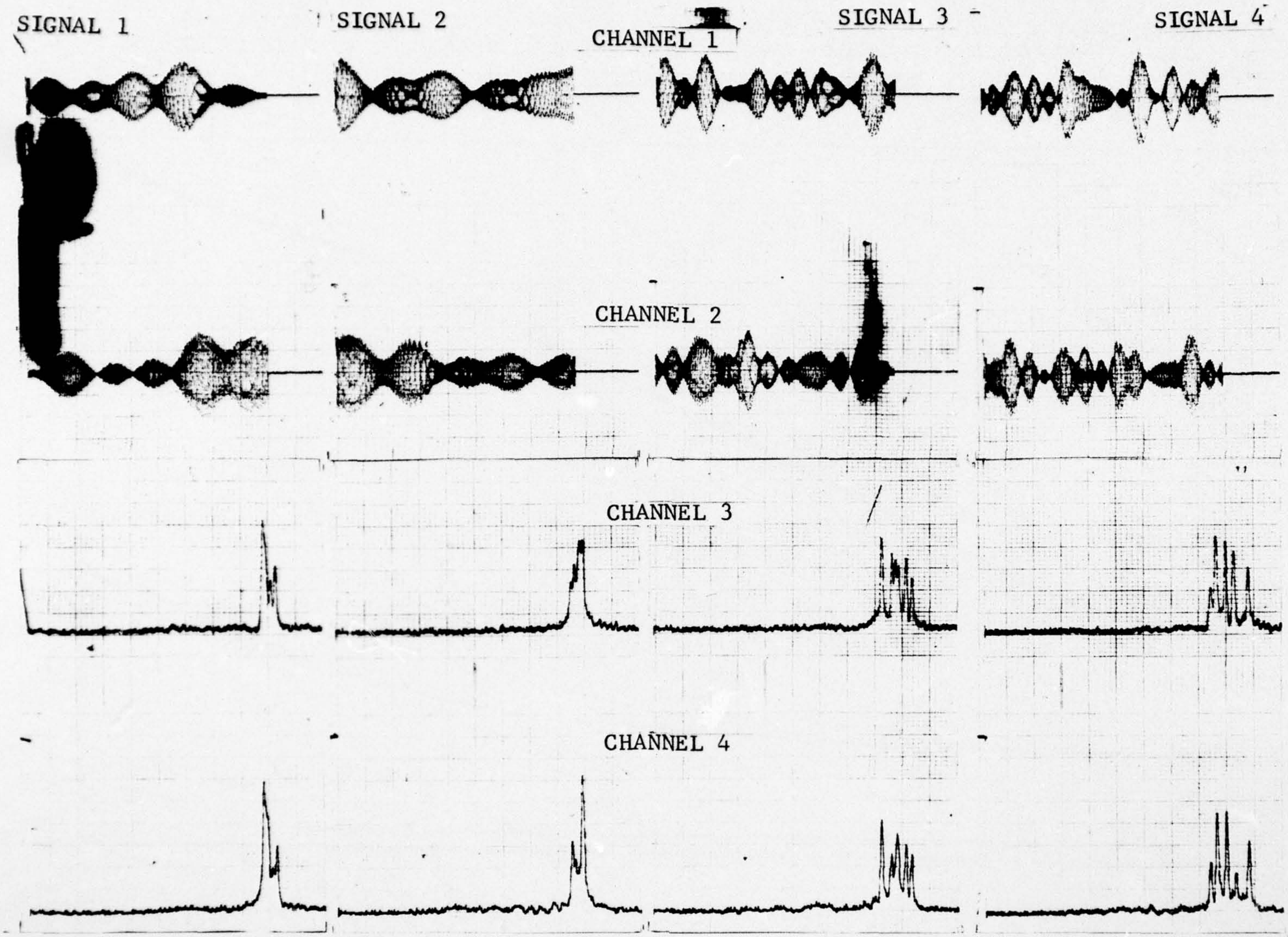

FIG. 45 FOUR TYPICAL PAIRS OF JITTERED FM SLIDE SIGNALS AND THEIR CORRELOGRAMS. CHANNELS 1 AND 3 ARE IDENTICAL TO CHANNELS 1 AND 3 OF FIG. 43. CHANNEL 2 SHOWS UPSLIDING FM SIGNALS RUNNING FROM 300 CPS TO 400 CPS, AND CHANNEL 4 IS THE CORRELOGRAM OF CHANNEL 2.

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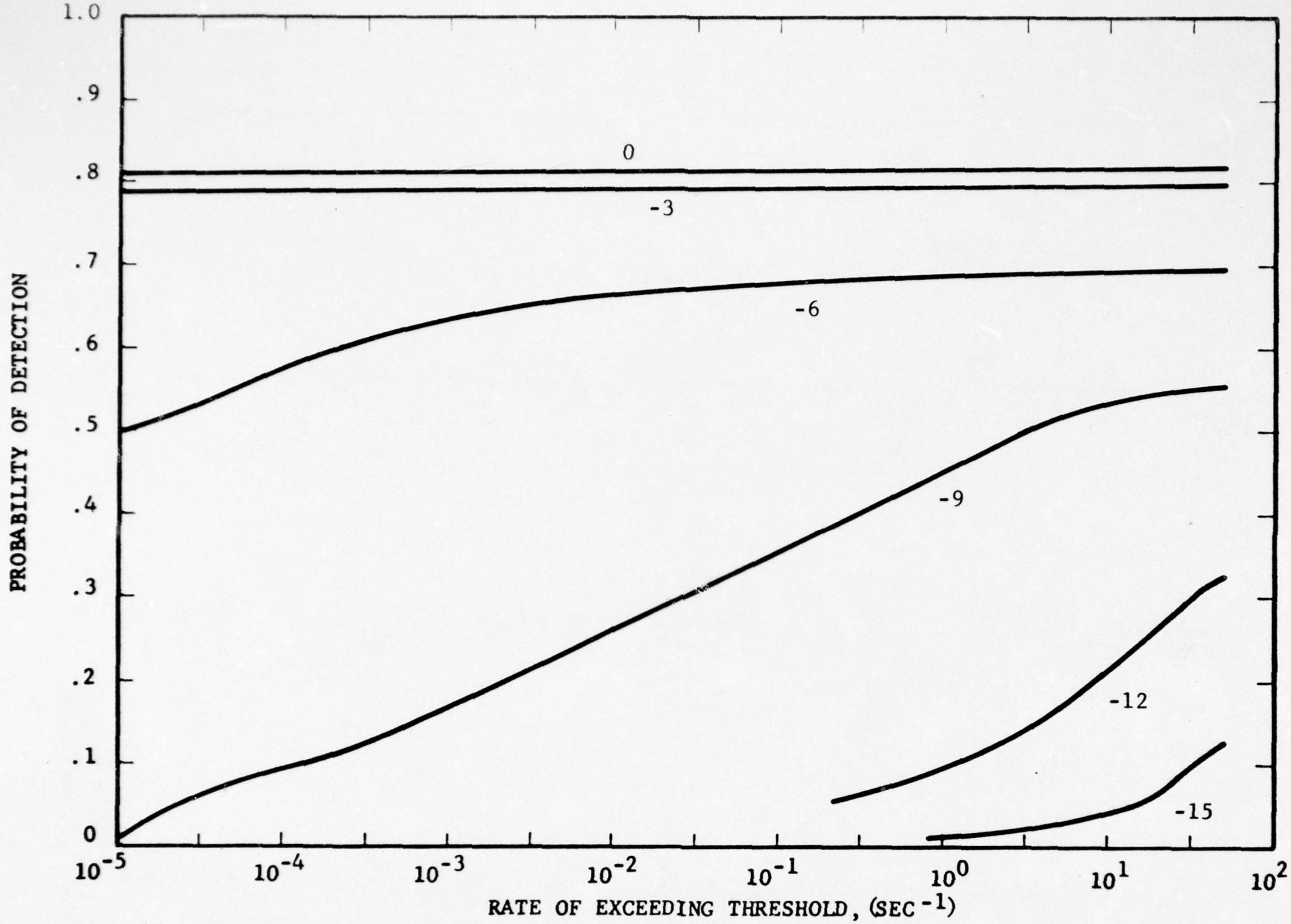

FIG. 46 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC JITTERED FM SLIDE SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. ALIGNMENT ACCURACY ±5 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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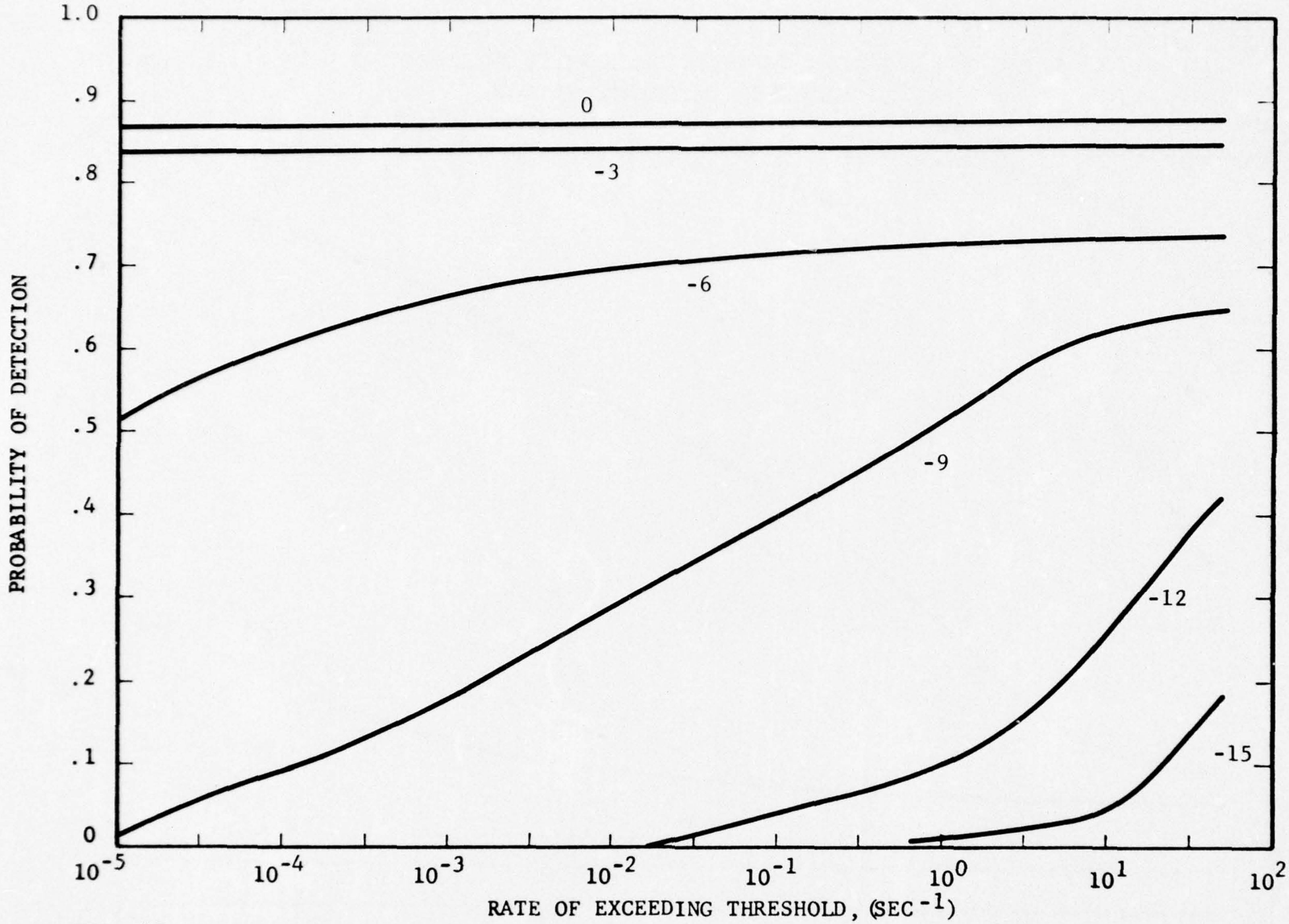

FIG. 47 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC JITTERED FM SLIDE SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. ALIGNMENT ACCURACY ±10 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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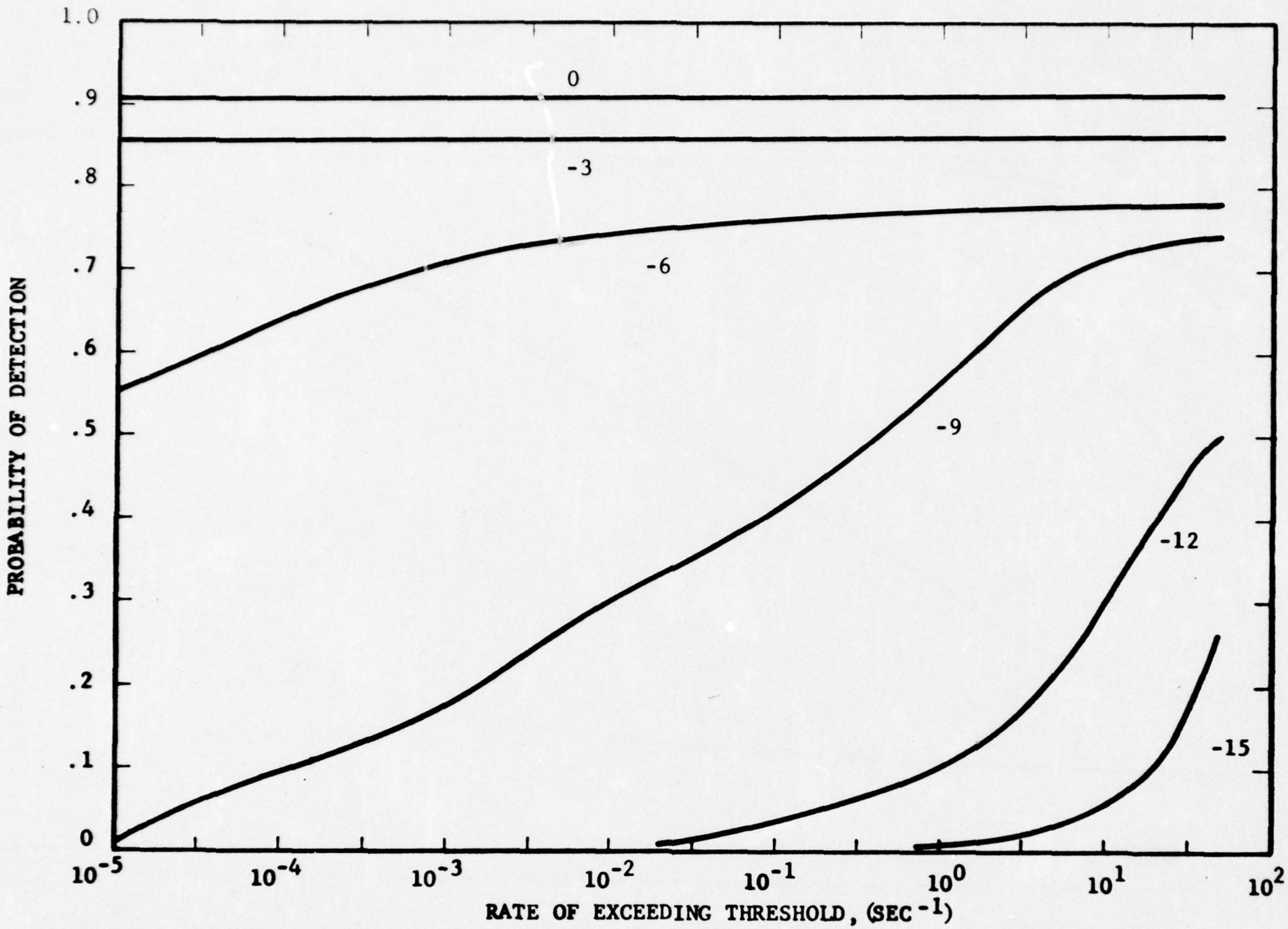

FIG. 48 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SEC JITTERED FM SLIDE SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. ALIGNMENT ACCURACY ±20 MILLISECONDS. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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large improvements noted in these curves over Figs. 41, 42, and 43 are directly attributable to this mismatched structure problem. Figure 49 was obtained from Figs. 46, 47, and 48. This gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate, for the process described by these three curves.

2.4 Cross Correlation of the Outputs of Two Replica Correlators Each of Which Operates on Half of a 2 Second, 200 cps FM Slide Signal

The first part of this processor consists of two linear replica correlators. The reference on one correlator is a 100 cps FM slide running from 200 cps to 300 cps, and the reference on the other correlator is a linear FM slide running from 300 cps to 400 cps. The output of each correlator is linearly rectified and averaged for 10 milliseconds. The output of the first averager is delayed by 1 second and the two channels are then cross correlated. This consists of a sample by sample cross multiplication and a further averaging process. Four values of averaging time were used in the final averager: 10 milliseconds, 20 milliseconds, 40 milliseconds, and 80 milliseconds. The first signals run were ideal linear FM slide signals running from 200 cps to 400 cps for the duration of 2 seconds. The modified ROC curves for the four different averaging times are shown in Figs. 50, 51, 52, and 53. Figure 54 was obtained from Figs. 50, 51, 52, and 53. This figure gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold crossing rate for the four values of averaging time. The performance of this processor on ideal signals is quite similar to a full linear replica correlation. Figure 55 shows plots of threshold crossing rate vs threshold setting for the four averaging times used. The 200 cps jittered FM slide signals were also run through this process. The four sets of

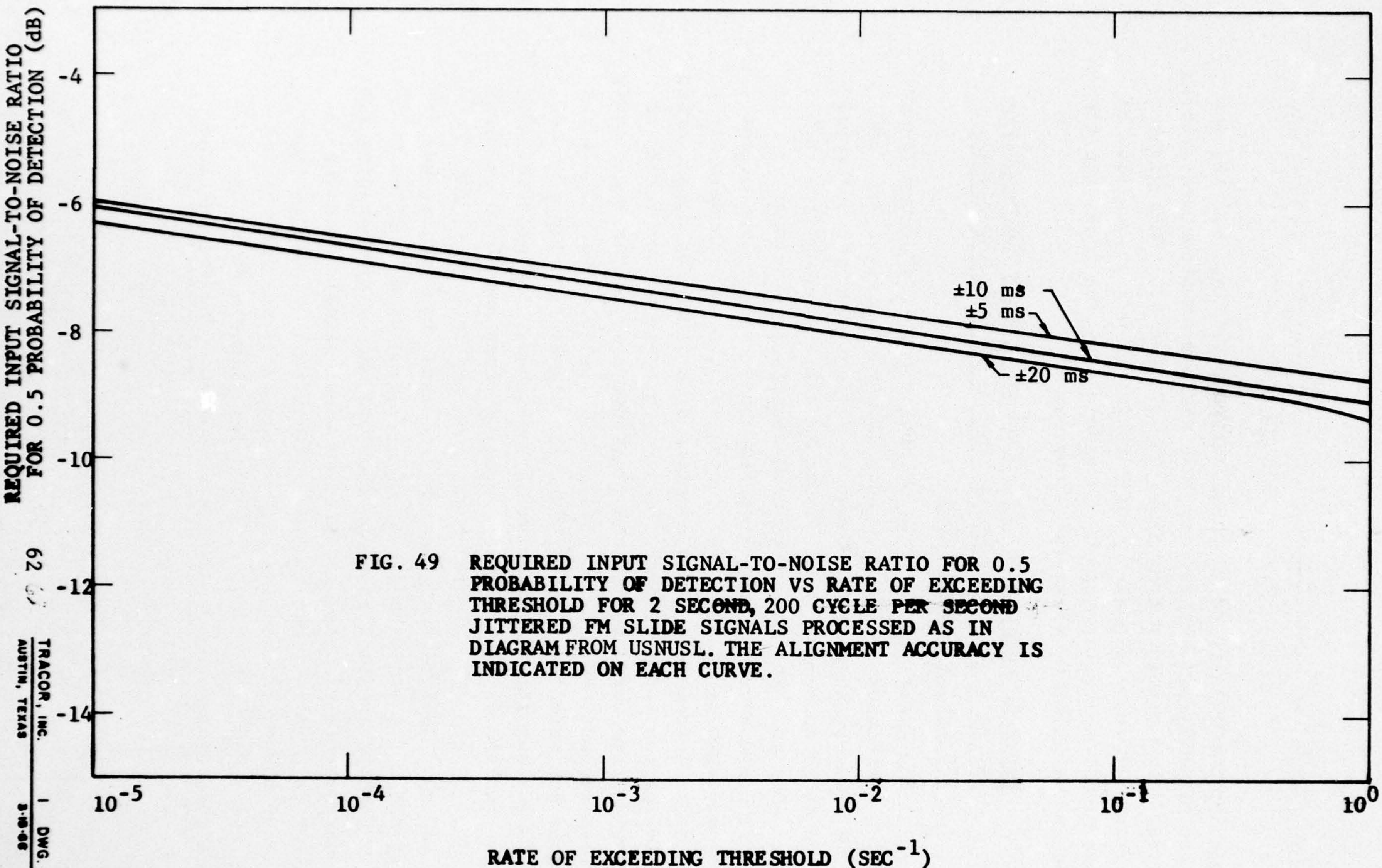

FIG. 49 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 2 SECOND, 200 CYCLE PER SECOND JITTERED FM SLIDE SIGNALS PROCESSED AS IN DIAGRAM FROM USNUSL. THE ALIGNMENT ACCURACY IS INDICATED ON EACH CURVE.

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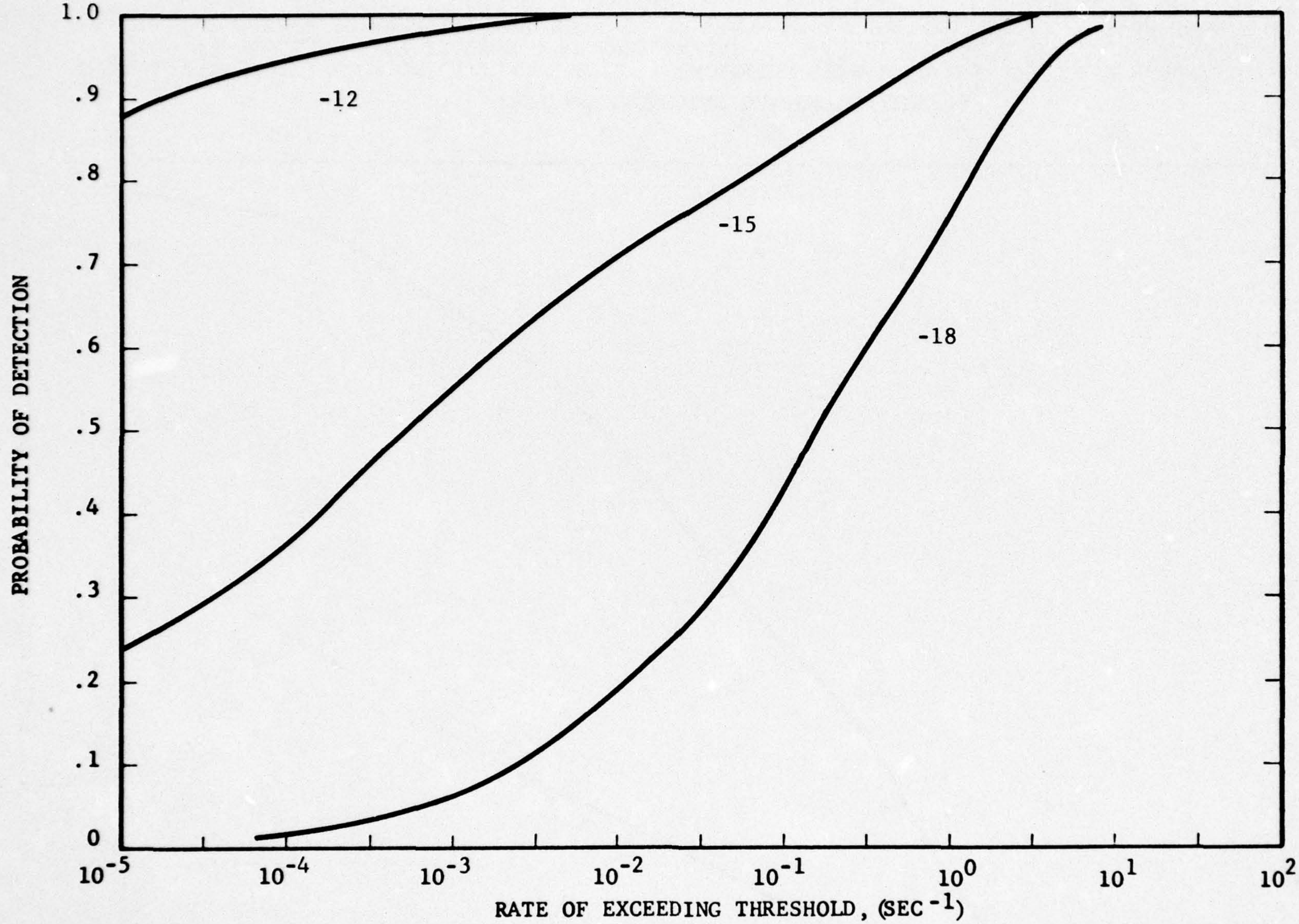

FIG. 50 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND IDEAL FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 10 MILLISECONDS WAS USED. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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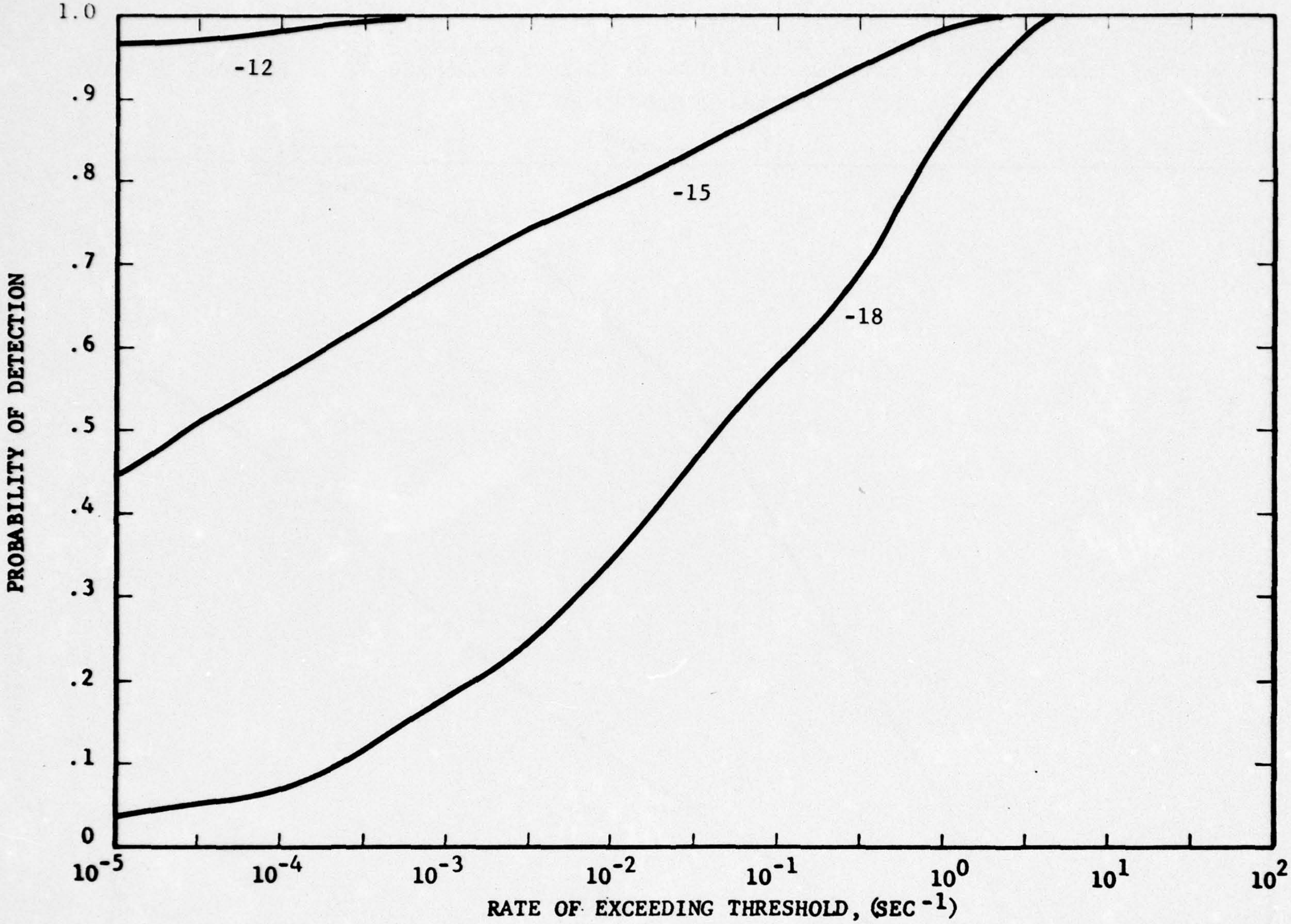

FIG. 51 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND IDEAL FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 20 MILLISECONDS WAS USED.. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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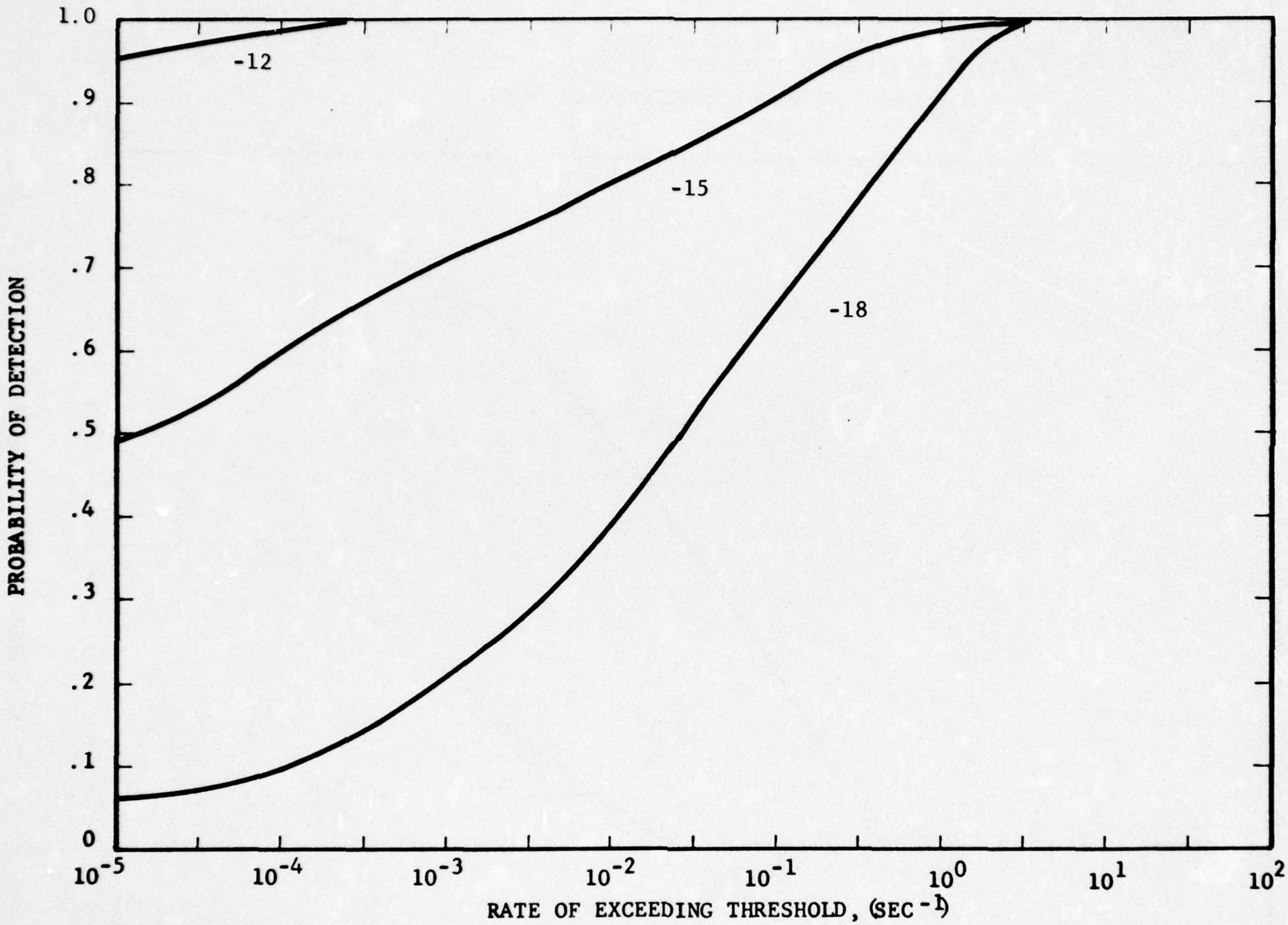

FIG. 52 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND IDEAL FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 40 MILLISECONDS WAS USED.. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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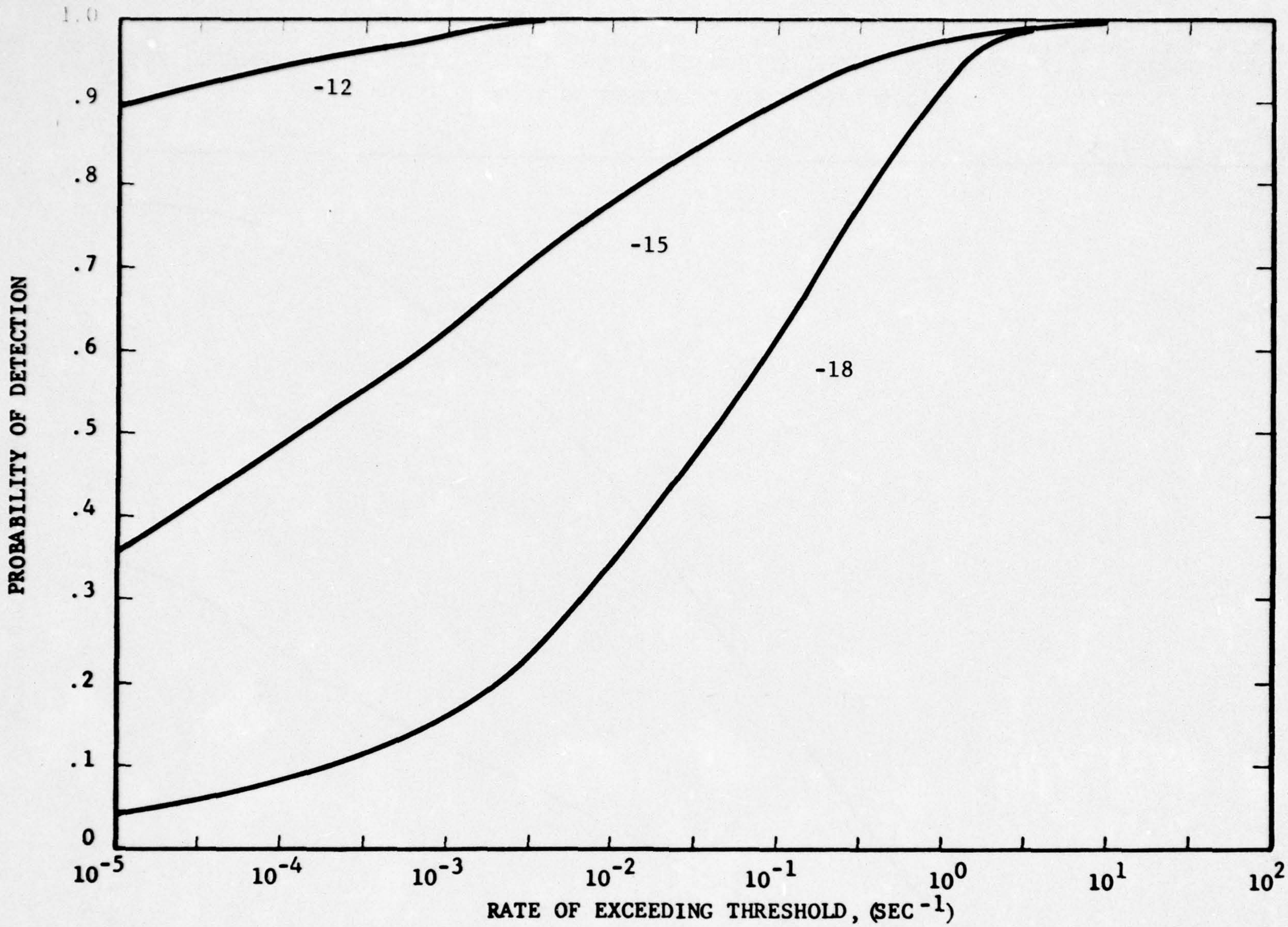

FIG. 53 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 ~~SECOND~~ IDEAL FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 80 MILLISECONDS WAS USED. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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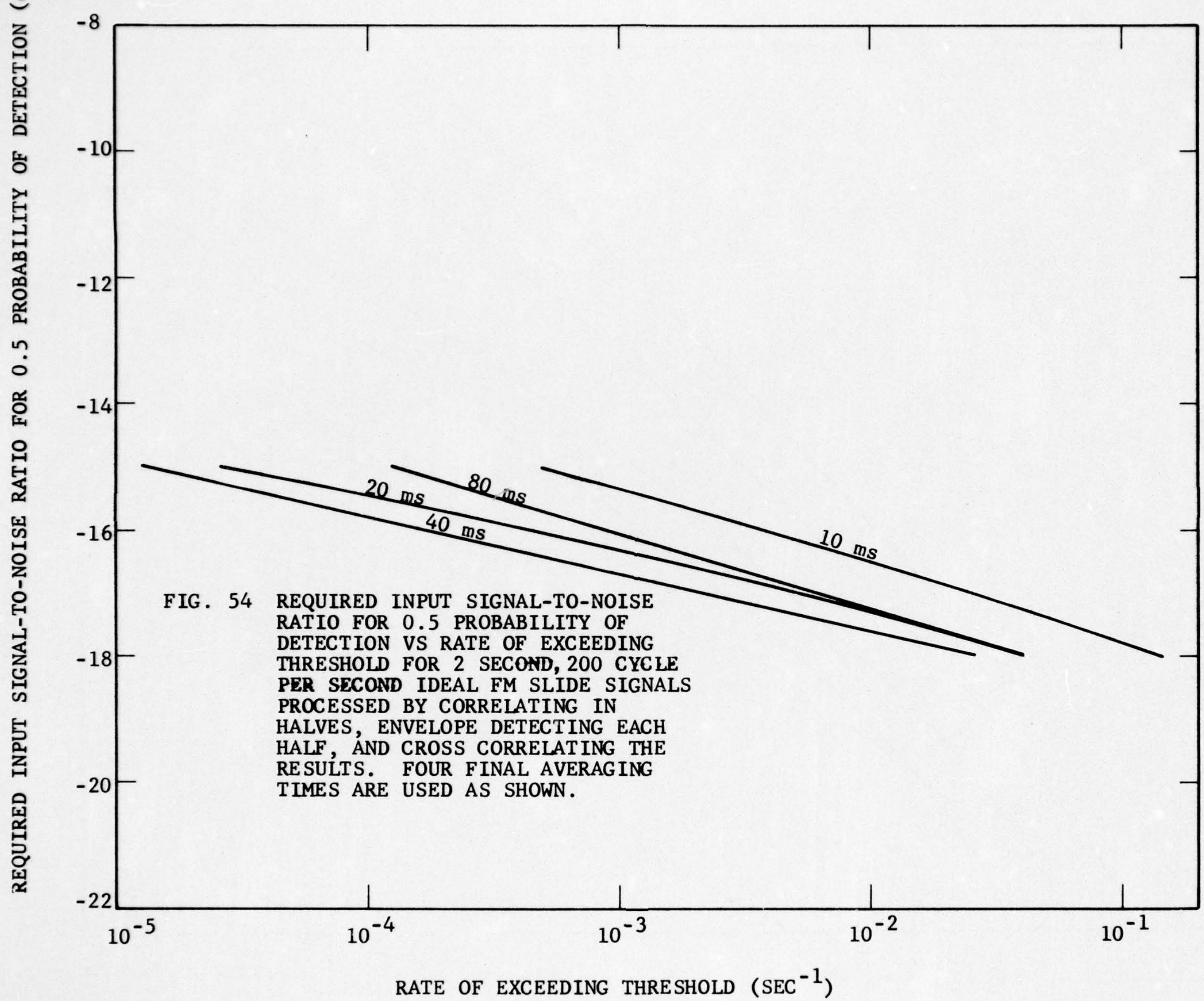

FIG. 54 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 2 SECOND, 200 CYCLE PER SECOND IDEAL FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. FOUR FINAL AVERAGING TIMES ARE USED AS SHOWN.

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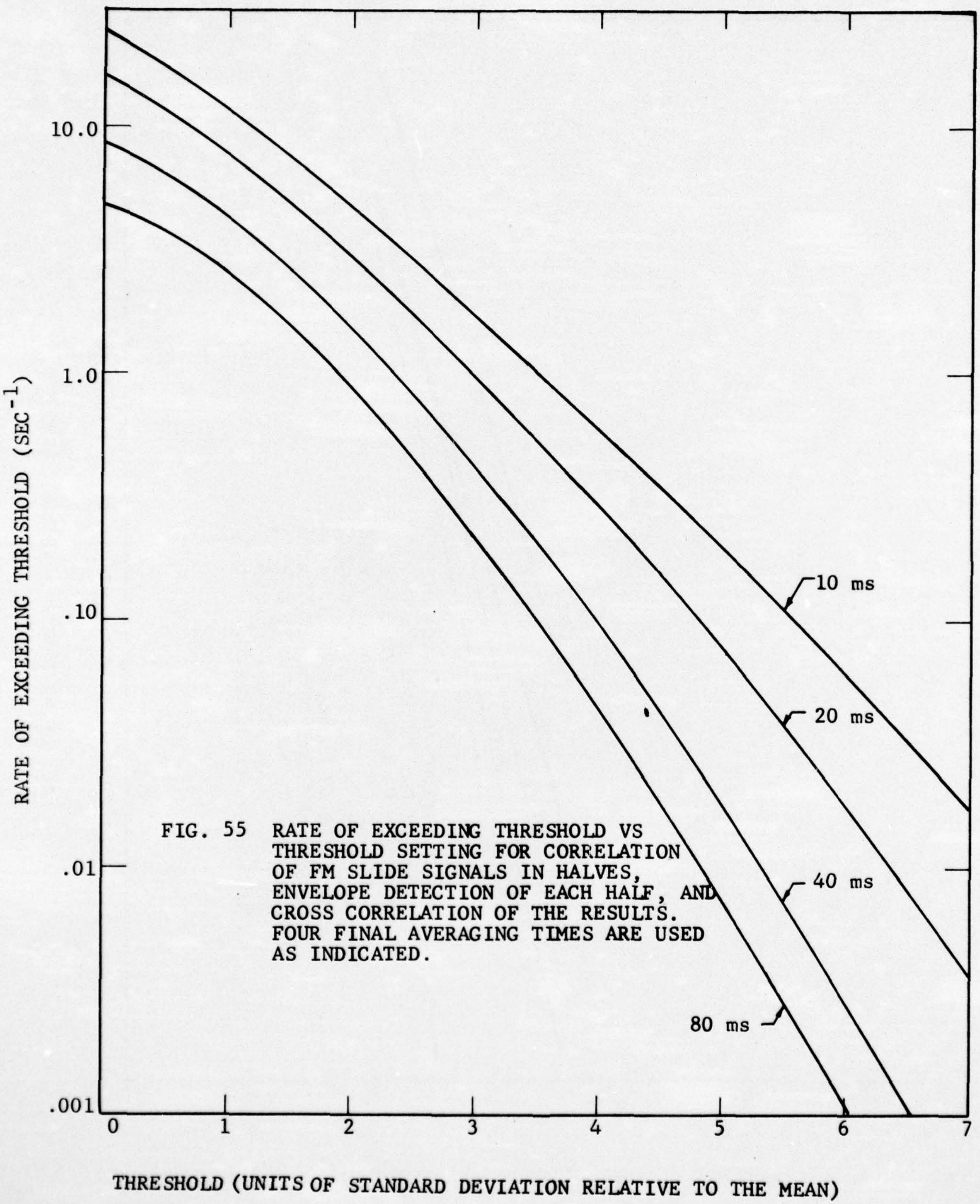

FIG. 55 RATE OF EXCEEDING THRESHOLD VS THRESHOLD SETTING FOR CORRELATION OF FM SLIDE SIGNALS IN HALVES, ENVELOPE DETECTION OF EACH HALF, AND CROSS CORRELATION OF THE RESULTS. FOUR FINAL AVERAGING TIMES ARE USED AS INDICATED.

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modified ROC curves for this application are shown in Figs. 56, 57, 58 and 59. Figure 60 gives the required input signal-to-noise ratio for 0.5 probability of detection as a function of the threshold rate. These curves were obtained from Figs. 56, 57, 58, and 59.

2.5 Summary of Jittered Signal Results

Figure 61 is a plot of required input signal-to-noise ratio for 0.5 probability of detection vs threshold crossing rate for the various processors operating on the jittered signals. The full correlation and the correlation by partial sums in two pieces gave practically the same performance. It is not too surprising that two piece correlation by partial sums did not have any advantage over the full correlation since the range and Doppler resolutions remaining in the 1 sec, 100 cps half-signals were still quite adequate to resolve each of the peaks in most of the signals. In the case of the eight-piece partial sums correlation, however, definite improvement is apparent. The cross correlation of the two correlator outputs showed a slight improvement over the full correlation, and the DRTFM processor, for reasons outlined above, did not succeed in detecting 0.5 of the signals at even the zero dB input signal-to-noise ratio.

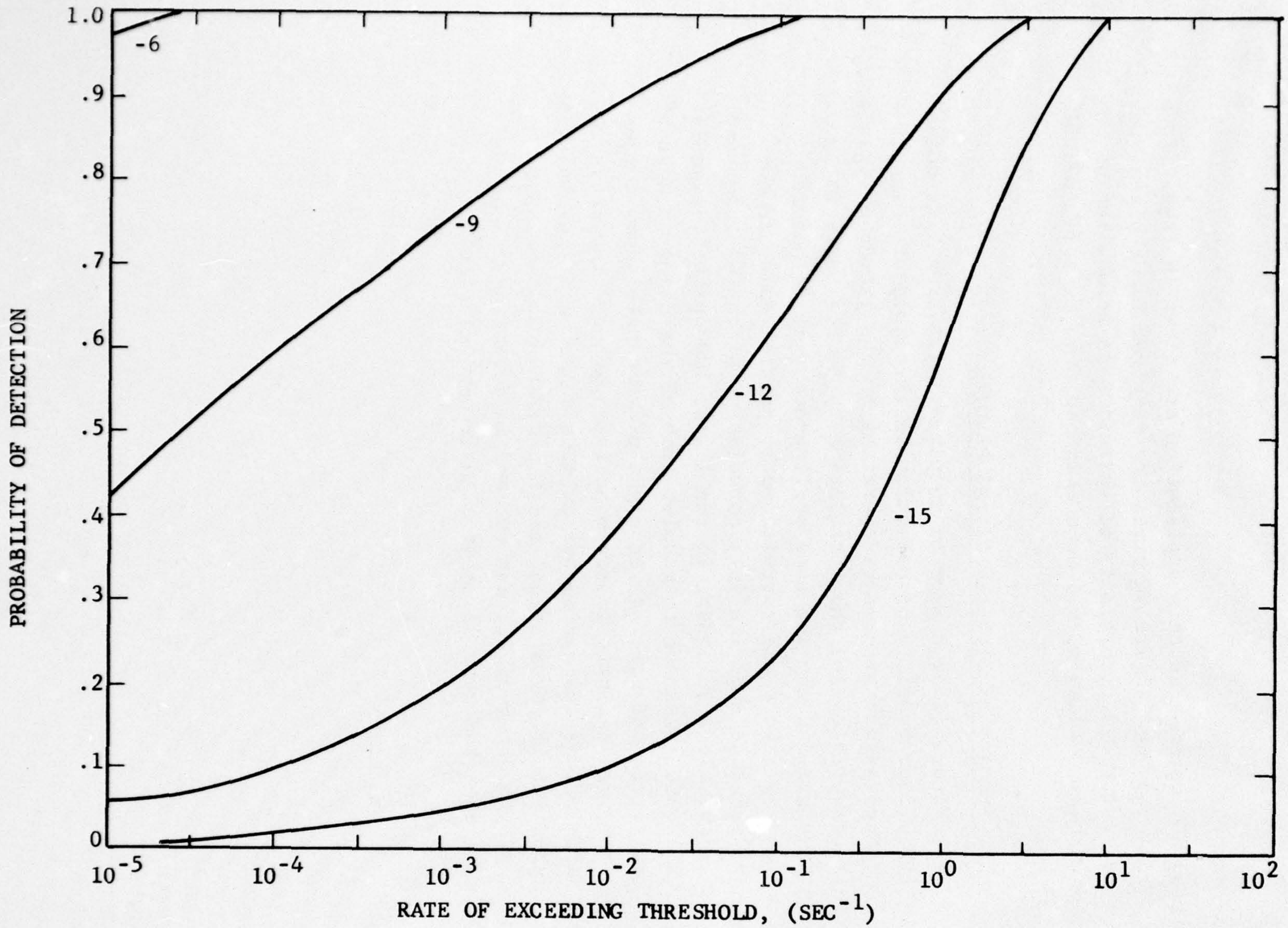

FIG. 56 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 ~~SECOND~~ JITTERED FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 10 MILLISECONDS WAS USED. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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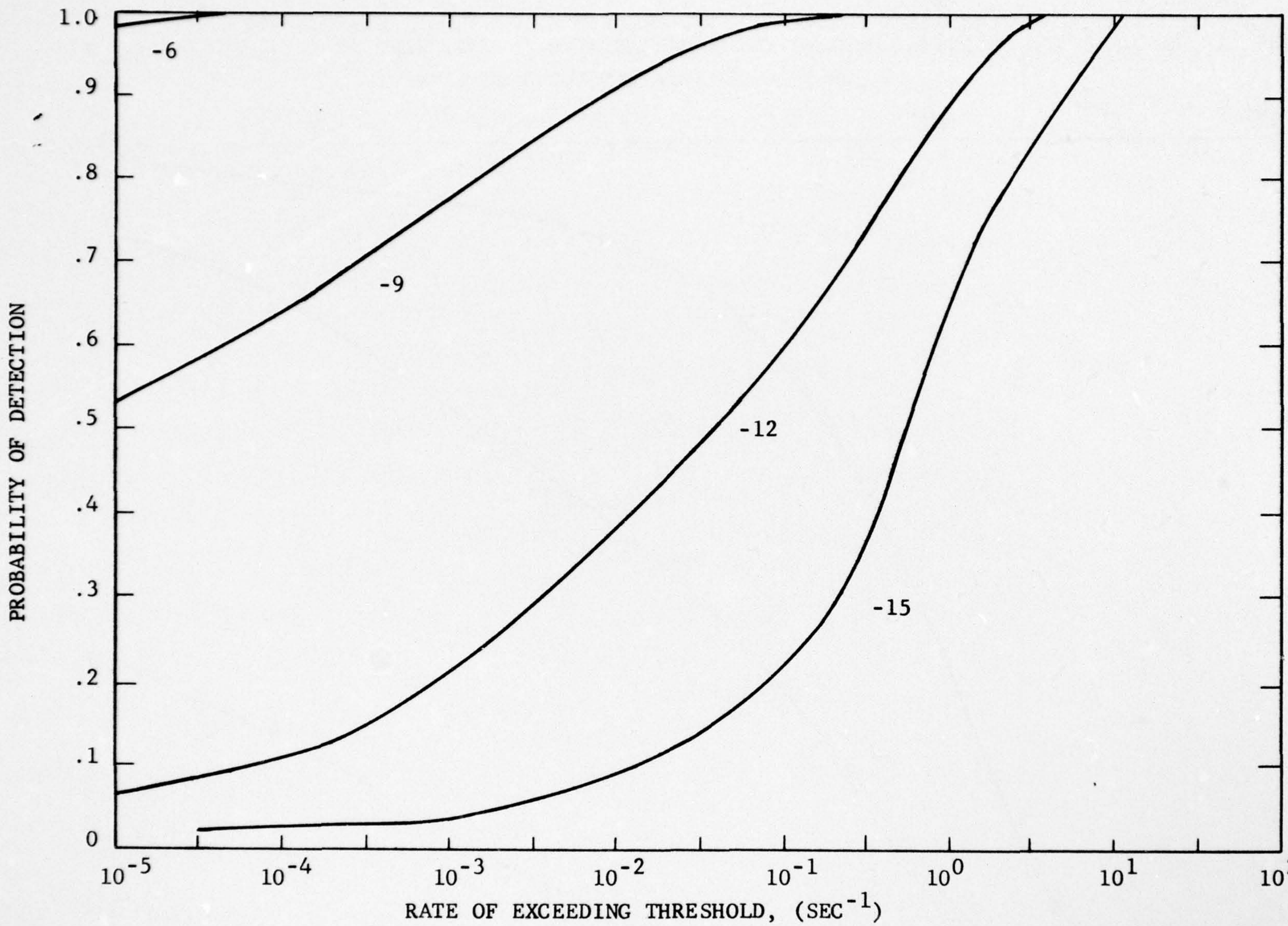

FIG. 57 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 ~~SECOND~~ JITTERED FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 20 MILLISECONDS WAS USED. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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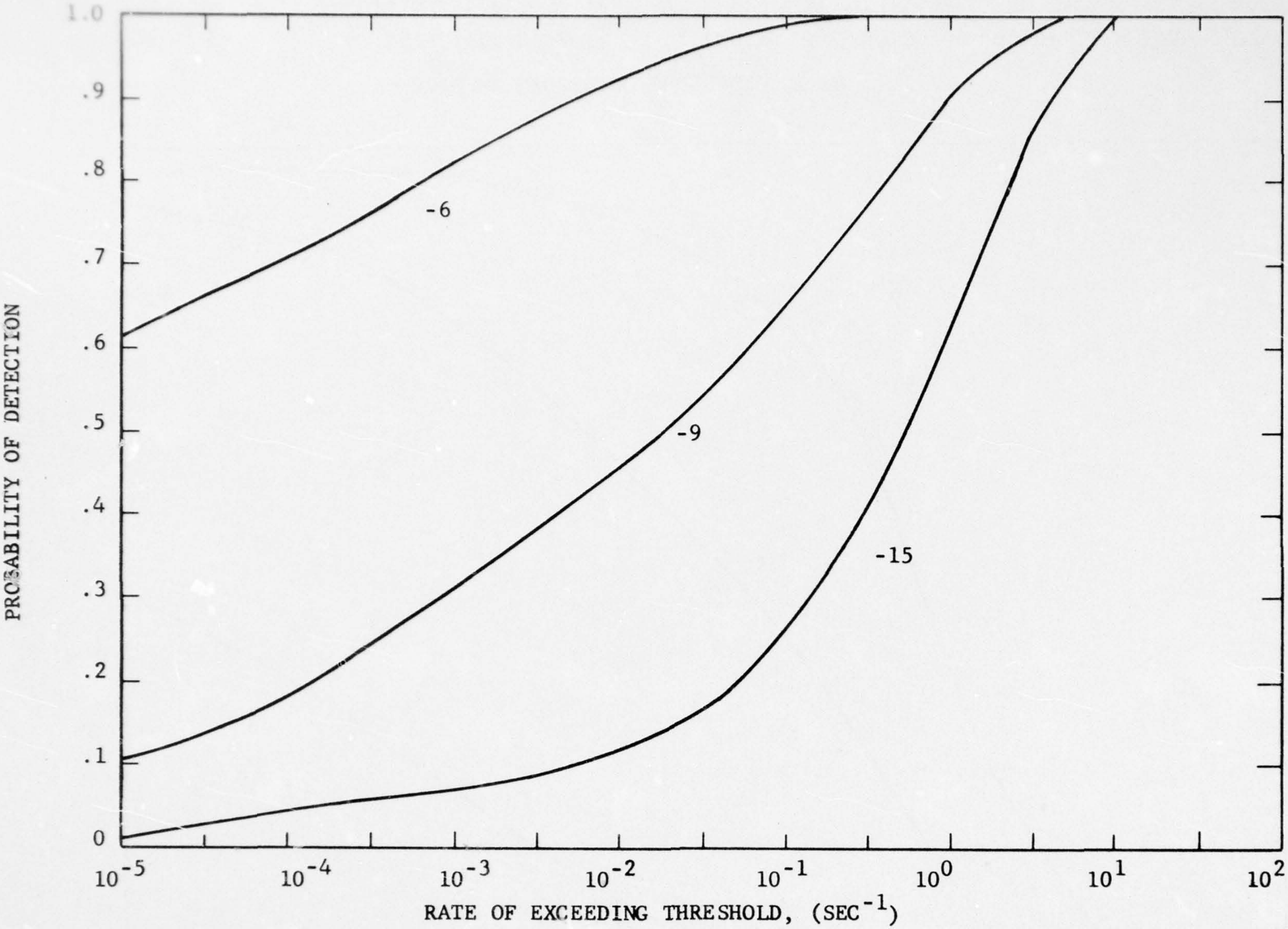

FIG. 58 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND JITTERED FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 40 MILLISECONDS WAS USED. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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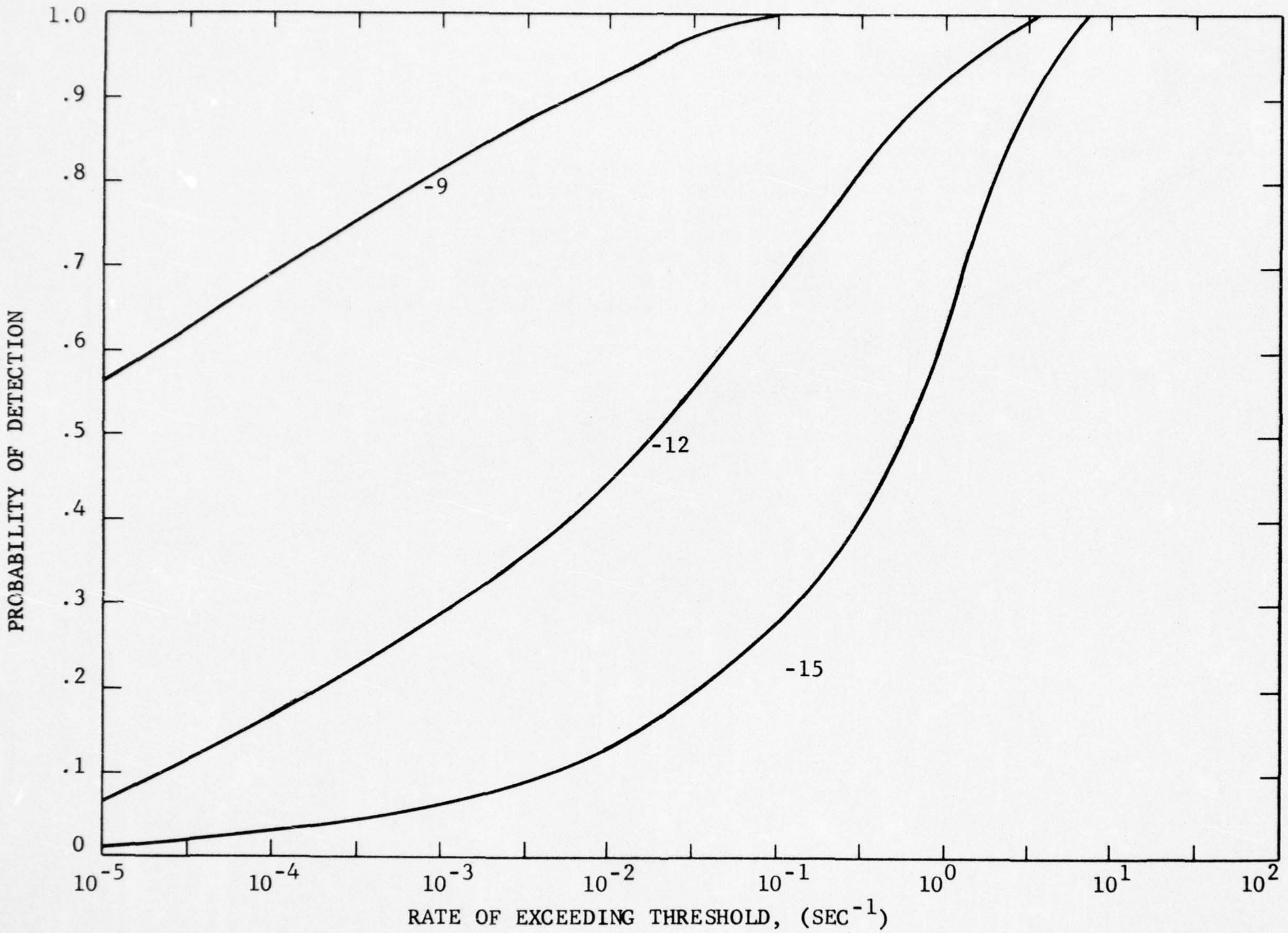

FIG. 59 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 200 CPS, 2 SECOND JITTERED FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. A FINAL AVERAGING TIME OF 80 MILLISECONDS WAS USED. THE INPUT SIGNAL-TO-NOISE RATIOS ARE INDICATED FOR EACH CURVE IN dB.

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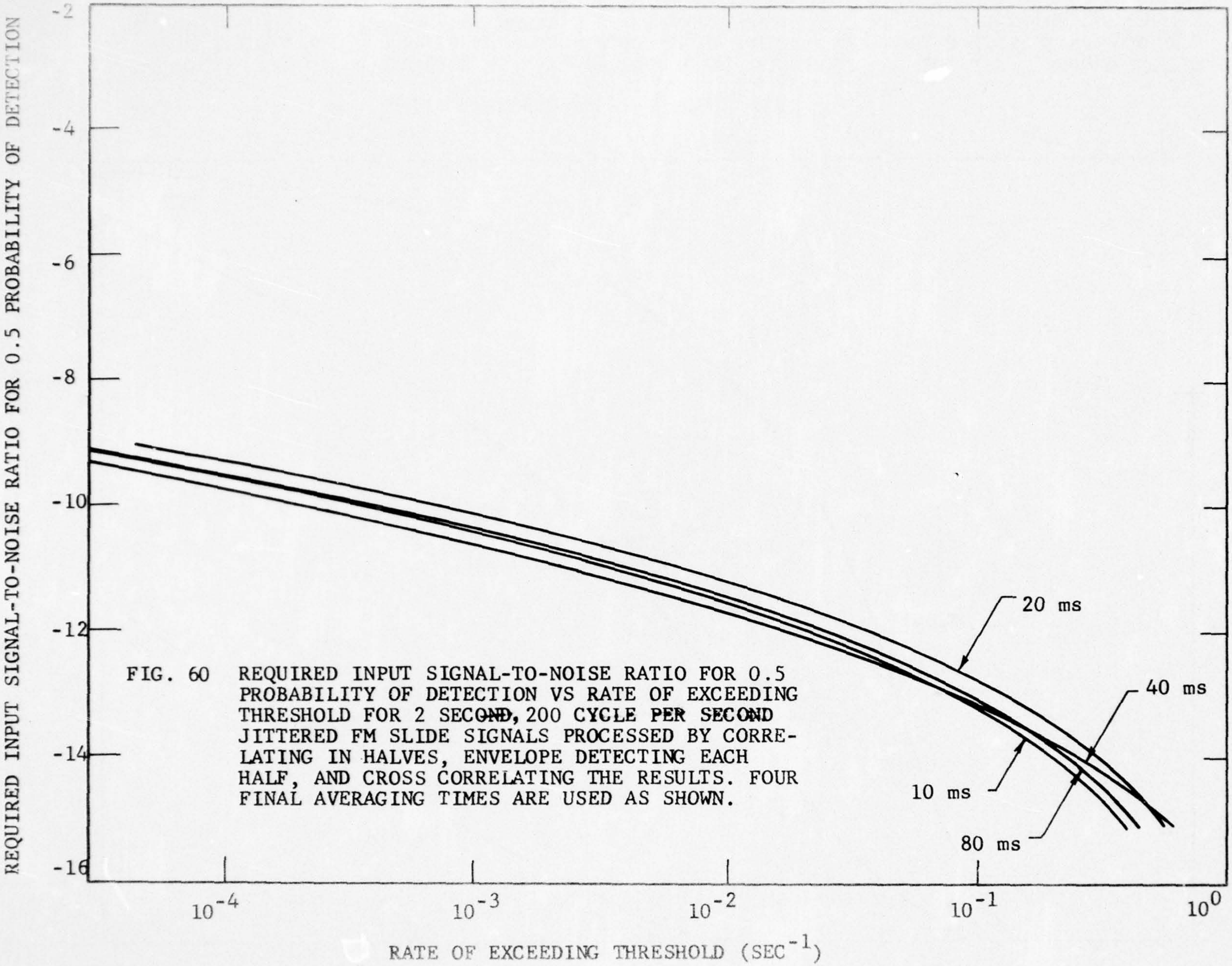

FIG. 60 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THRESHOLD FOR 2 ~~SECOND~~ SECOND, 200 CYCLE PER SECOND JITTERED FM SLIDE SIGNALS PROCESSED BY CORRELATING IN HALVES, ENVELOPE DETECTING EACH HALF, AND CROSS CORRELATING THE RESULTS. FOUR FINAL AVERAGING TIMES ARE USED AS SHOWN.

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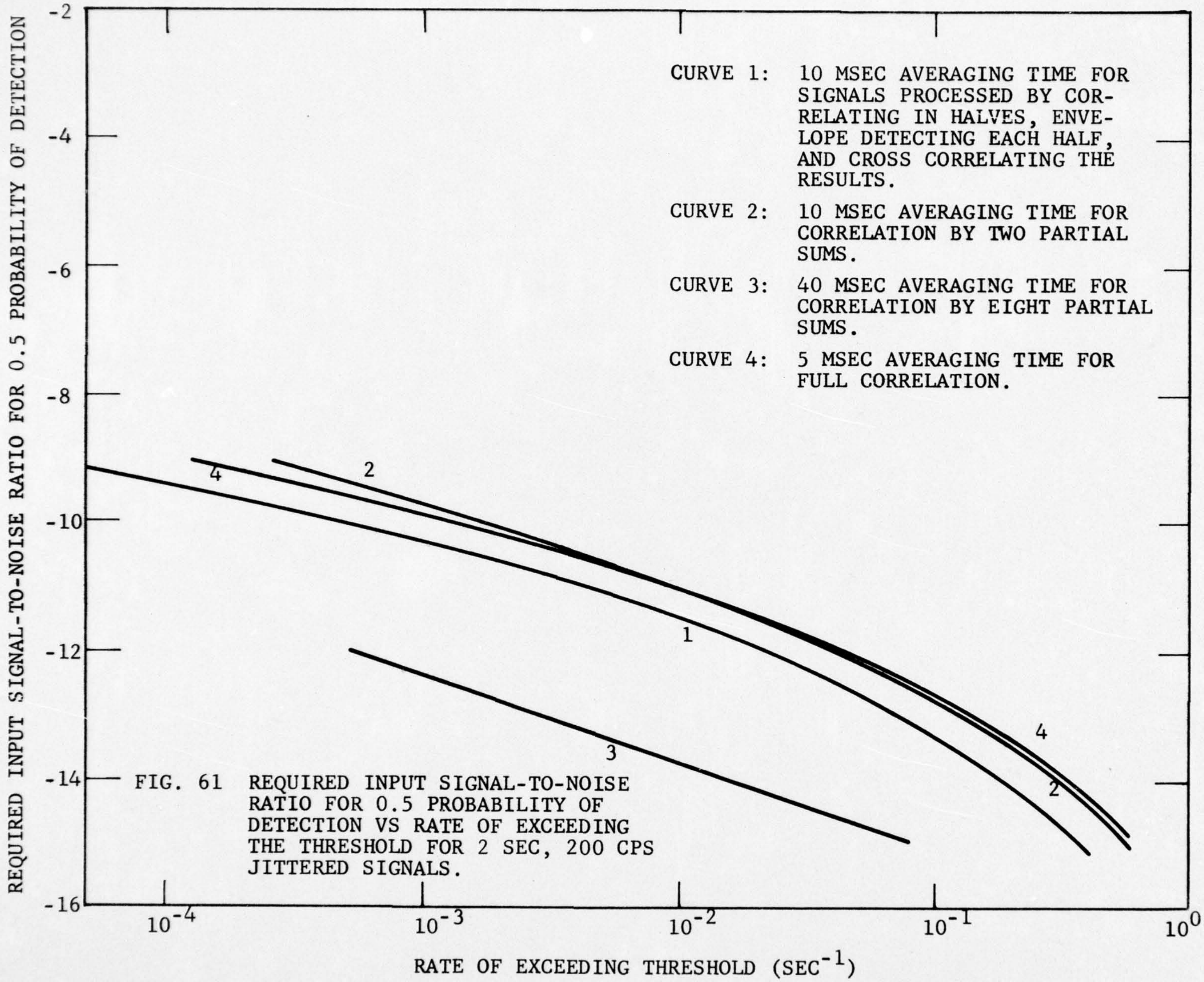

FIG. 61 REQUIRED INPUT SIGNAL-TO-NOISE RATIO FOR 0.5 PROBABILITY OF DETECTION VS RATE OF EXCEEDING THE THRESHOLD FOR 2 SEC, 200 CPS JITTERED SIGNALS.

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